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FLEXIBLE DESIGN AND MANUFACTURING SYSTEMS FOR AUTOMOTIVE COMPONENTS AND SHEET METAL PARTS

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13. ABSTRACT *(Maximum 200 words)*

The objective of this effort was to improve manufacturing flexibility by developing a systematic approach to improving the product-process design methodology using transactions analysis and feature-base methods of computer system and database design for the automotive components and sheet metal operations.

The first two-and-a-half sections of this report duplicate to a significant degree the report submitted by the sister project Fast and Flexible Communication of Engineering Information in the Aerospace Industry, because this work was executed in a nearly seamless fashion. The later sections of this report provide outputs distinct from those reported by the sister project, although many of the insights cannot be easily traced to one of the projects to the other's exclusion.

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Fast and Flexible Design and Manufacturing Systems for Automotive Components and Sheet Metal Parts

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Foreward

This is the final report on the program Fast and Flexible Design and Manufacturing Systems for Automotive Components and Sheet Metal Parts, Air Force Contract number F33615-94-C-4428, administered by Wright Laboratory/MTIA. Mr George Orzel served as Air Force Program Manager. The period of performance was June 17, 1994 through January 31, 1998. This program was funded as part of DARPA's effort in Agile Manufacturing, under the direction of Dr Michael McGrath. The prime contractor was the Massachusetts Institute of Technology. The work was conducted by members of the MIT Mechanical Engineering Department, the MIT Sloan School of Management, and the MIT Center for Technology, Policy, and Industrial Development, as well as the Lehigh University Mechanical Engineering Department. The Principal Investigator was Prof Charles Fine. Participating organizations included the Ford Motor Company, Ford Visteon Electronics Division, General Motors Delphi Saginaw Division, General Motors Mid-Lux Division, and General Motors Die Management Group. This program shared some participants with a sister program called Fast and Flexible Communication of Engineering Information in the Aerospace Industry: The Vought Center of Northrop-Grumman Corp, Boeing Commercial Airplane Group, and Lockheed-Martin Ft Worth Division. Technical contributions were made by Mr Martin Anderson, Mr Carlo Cadet, Prof Charles Fine, Prof David Gossard, and Dr Daniel Whitney, plus graduate students Min Ho Chang, Narendra Soman, Amit Dhadwal, Renata Pomponi, Don Lee, Brian Kelley, Richard Keiser, Neetu Bhatia, Paul Gutwald, Geoffrey Parker, and Sharon Novak. Administrative support was provided primarily by Gina Milton. The first two-and-a-half sections of this report duplicate to a significant degree the report submitted by the sister project, Fast and Flexible Communication of Engineering Information in the Aerospace Industry, because this work was executed in a nearly seamless fashion. The later sections of this report provide outputs distinct from those reported by the sister project, although many of the insights cannot be easily traced to one of the projects to the other's exclusion. The companion final report of the Lehigh component of the automotive project was compiled by Professor Mikell Groover and submitted under separate cover.

Executive Summary

This program was launched together with a sister program called Fast and Flexible Communication of Engineering Information in the Aerospace Industry to explore ways of improving the design and manufacture of complex products in an environment of globalization, outsourcing, information technology, increased international competition, and shrinking defense budgets. The research was conducted in the context of Agile Manufacturing, which seeks to improve the performance of companies operating together in fast-changing environments. The opportunity to conduct research on the seemingly disparate auto and aircraft industries proved to be very beneficial, because it was found that these industries share many of the same problems and can learn a great deal from each other.

Both the Auto and Aero programs focused on the design, development, and manufacture of complex electro-mechanical assemblies such as automotive bodies, electronic assemblies, and aircraft structure. Such products challenge their manufacturers because they have many parts, tight tolerances, and high performance standards. It is common that 50 to 75% by value or part count is outsourced. In spite of great progress in computer-aided design (CAD) and information technology (IT), problems still occur on the assembly line during production ramp-up and daily production.

Mechanical assemblies are a good focus for this kind of research because they exhibit what may be called *integration problems*. Assembly is inherently integrative, and assembly problems are proxies for a wide variety of technical, organizational, and managerial problems encountered in the design and manufacture of high technology products in the military and commercial worlds. What we learn about improving the design of assemblies can be translated to a considerable degree to other highly integral products.

A basic assumption behind this project is that factory floor problems can often, perhaps mostly, be traced to errors or missing information stemming from product design. Important goals of this project were therefore to improve the agility of manufacturing companies by determining what this missing information might be, documenting the technical and managerial efforts companies are using to provide and utilize this information, understanding the barriers to improved methods, and developing new methods based on research that is grounded in case studies with partner companies.

From the basic assumption, we developed our research approach, which began in every partner company with projects on the factory floor. Here we learned about actual assembly problems and traced some of them to their causes. We also documented the corrective action processes at different companies and compared not only their content but the degree to which corrective action personnel could draw on design data to help them solve their problems. Finally, we developed some new analysis and design methods.

Here are some of the specific problems and observations that came from our efforts:

Product design in the auto and aircraft industries takes from 3 to 10 years and may involve companies thousands of miles apart; a great deal of information is created and exchanged during this time, and the opportunity for errors is large

There is a wide range of performance between the companies in the auto industry and the aircraft industry in the design and procurement of complex assemblies, with adoption of best practices in the auto industry leading that in the aircraft industry by as much as 7 years

Key design decisions that affect assembly floor performance (speed, rework time, first time yield, cost) are made as early as the concept design phase, but these decisions may occur unconsciously or as unseen parts of other decisions; once the design process passes to later phases, it operates within the chosen concept for good or ill, and there is little opportunity to change it

Companies that develop and partially outsource complex products face what we call "integration risk:" the risk that apparently correctly designed and made components will not function together properly as a system; companies lack adequate tools to identify integration risk during concept design, the time when decisions that create this risk are made

Integrated product teams (IPTs) consist of people from very different technical and non-technical backgrounds, and their contributions during concept design in particular span a very wide range of strategic, tactical, business, and technical issues; these people lack a common language for dealing with many key concept design issues

Any new computer tools that intend to aid IPTs in addressing issues with high leverage on agility will have to be understandable by all IPT members regardless of their functional background

Product and Process Development, executed jointly and often called Concurrent Engineering, although providing a great leap in performance over older "throw the design over the wall to manufacturing" approaches, can be improved even further, by integrating Supply Chain Development into what we call "Three-Dimensional Concurrent Engineering."

Because automotive and aerospace products are so complex, extensive supply chains are required to support the work done by the large integrator companies like

Ford, GM, Boeing, and Lockheed-Martin. Companies can improve their prospects for competitive success significantly by proactive design of these supply chains that considers long-term strategic effects as well as tactical, programmatic needs.

The automotive and aerospace industries and their supply chains evolve fairly slowly compared with some other industries such as consumer electronics and telecommunications. By studying the evolution of these "faster clockspeed" industries, numerous insights can be found for supply chain considerations in the automotive and aerospace industries.

To address these issues, the program conducted the following research and case studies:

1. Historical study of the development of assembly dimensional control methods in the auto industry, with emphasis on the combination of technical, organizational, and managerial elements necessary for successful implementation (Section 2)

2. Development of mathematical and computer models for sheet metal assemblies focused particularly on compliant parts (Section 3)

3. Development of the "industry clockspeed"concept to speed learign about automotive and aerospace supply chain development by studying the supply chain dynamics of faster-evolving industries (Section 4)

4. Development of a methodology for "strategic supply chain design" to help companies consider the long-term implications of the suppy chain choices they make (Section 5)

5. Development of an approach and tools for "Three-Dimensional Concurrent Engineering" (3-DCE) to help companies integrate supply chain design and development with their concurrent product and process development tools and activities. (Sections 6 and 7)

6. Development of an integrated approach to combining the clockspeed, strategic supply chain design, and Three-Dimensional Concurrent Engineering concepts (Section 8)

7. Creation of a new course in Three-Dimensional Concurrent Engineering, incorporating many of the lessons and new methods that emerged from this program (Section 9)

1. Introduction

1.1 Motivation and History

1.1.1 Agile manufacturing

The aim of this program was to apply some of the principles of Agile Manufacturing [Goldman, Nagel, Preiss] to problems of large scale manufacturing of complex products. One of the aims of Agility is to improve communications between customers and suppliers. It is apparent that these communications are presently hampered by a lack of reliable technologies for exchanging files in common formats. Although progress is being made on this front, it is also true that other problems exist that cannot be solved even by perfect file exchange technologies. These problems exist not only at the technical level but also at the organizational and managerial levels. Design documents do not necessarily contain the necessary information. People with different functional backgrounds or organizational loyalties do not always share vocabularies and motivations, and thus either cannot really understand each other or may not be able to act appropriately.

Our goals in this research were to

Understand how to improve complex customer-supplier relationships, using assemblies as an example

Compare methods and performance of the auto and aircraft industries

Develop new methods and tools

Develop metrics

Test the tools and metrics in partner companies

This research was originally based on two hypotheses:

1. Important blockages of information flow can be identified by examining business processes and looking for places in the process that exhibit "interaction intensity"

2. Important technical information about mechanical and other items can be captured in "features" which are, at a minimum, standardized geometric elements with associated information about use, processing, etc.

In pursuit of the first hypothesis, we developed tools to map information flows and identify transaction intensity in a systematic way. In pursuit of the second hypothesis, we created methods of modeling complex assemblies and showed how their interactions could be captured during design and preserved for later participants in the process of bringing products to production. These are listed in Section 1.2.2 and explained in detail later in the report.

We see the causes of poor communication in two forms: either the information is corrupted at points of interaction intensity or else it is missing from the beginning. We see the consequences on the factory floor where it takes too long to assemble products, or there is too much rework, or it takes too long to ramp production up to full rate. However, we do not see this as the fault of the factory or its workers. Instead we see the problem stemming from the lack of critical information that should have been provided during the design process. (For example, [Ceglarek and Shi] report that 27% of root causes in 52 automotive body assembly problems were due to design related problems. During ramp-up, design-related problems accounted for 43%. Problems related to suppliers almost equal those due to design. Our own research produced similar results.)

Therefore, a restatement of the problem is: what is the missing information from design that contributes so much to loss of agility in the assembly of complex products? What we found is:

products are procured from a complex web of companies spread far apart geographically

this trend is accelerating

complex products contain hundreds of assemblies and thousands of parts, the majority of which are purchased from chains of distant suppliers who may design as well as make them

the problem facing any company in this chain is managing the process, including defining and managing interfaces among all the outsourced items

factors affecting the quality of a complex product arise from the design and operation of *sets* of parts, rather than from one or a few key parts

when a product fails to deliver the required quality, either during design, production ramp-up, or full rate production, it is extremely difficult to find out why because many parts or assemblies and many suppliers are involved, and a consistent, readily understood map of their interactions has not been created

Therefore, the key missing information revolves around descriptions of how sets of parts are intended to work together. Either the product was designed without planning the overall performance in a top-down way or else the design intent for achieving overall quality was not captured and communicated to the suppliers and final assemblers in sufficient form and detail to permit design, procurement, and assembly to proceed in a fast and flexible manner.

The above properties of modern product development and manufacturing are illustrated in Figure 1-1.

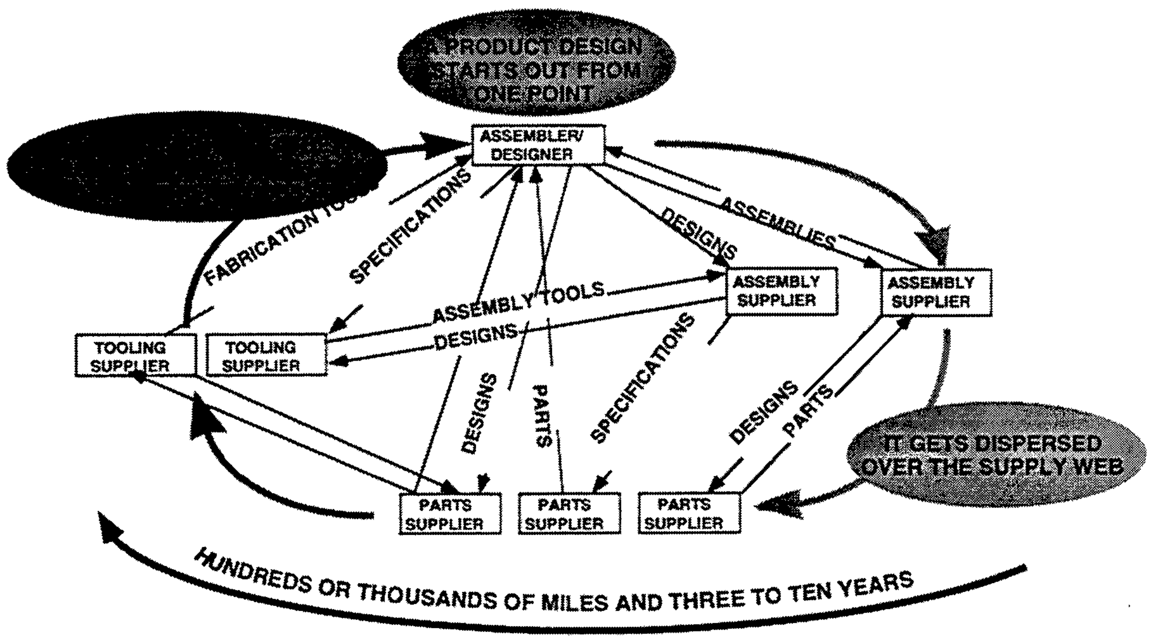

Figure 1-1. Complex Products Are Procured from a Complex Web of Companies. This web is not tiered and the items exchanged include information, things, and people.

1.1.2 Aero and auto programs at MIT

MIT has conducted studies on fast and flexible manufacturing in the auto and aircraft industries in parallel.[1] The benefit of having these two projects is the ability to share research methods, send students and research staff to companies in both industries, and compare findings. To a surprising degree, we find the same causes and effects in both industries. Both have large and far-flung supply chains, develop complex electro-mechanical products, work to a high standard of quality and tolerances, and have to create a complex but cost-effective and safe product. Both industries have been leaders in design technologies.

Again, to a surprising degree, the two industries share problems and solution methods. The major differences are that the auto industry may have a faster learning curve because it can design more products and can expose its design and

[1] The Aero program has prepared a separate final report.

manufacturing employees to more learning experiences in a given time. Furthermore, the car industry has a faster production rate and thus cannot ignore a factory floor problem for more than a few minutes, whereas the aircraft industry often takes weeks or months to recognize a problem and find a solution.

People in the aircraft industry often say that the car industry can invest more in design and production technology because of the benefit of high production rates. The situation is in fact the opposite: a high production rate forces the car industry to solve problems quickly and to develop the necessary technology.[2] In fact, as will be described below, we believe that in a number of areas the car industry is ahead of the aircraft industry:

organization of the product development process to create top-down dimensional control plans for assemblies,

managerial sophistication to form partnerships with suppliers of assemblies and the necessary equipment, tooling, and fixturing,

ability to follow up designs and plans,[3] and

use of systematic procedures for diagnosing and fixing assembly plant errors.

In fact, it is precisely because learning opportunities are fewer in the aircraft industry that it must do more during design to reduce integration risk.

1.1.3 Focus on procurement of complex mechanical assemblies from a supply chain

To limit the scope of this research without losing generality, we focused on complex mechanical assemblies. Assemblies share many of the properties of systems in general. They have many components which work together in complex ways to create the system's overall behavior. More importantly, they share with systems in general the property of *non-co-location of cause and effect*, which means simply that the symptom can be here while the cause is "way over there." One of the major cultural barriers to improving speed and flexibility in procurement of assemblies is to convince people that a problem in an assembly is not the fault of the last part installed. A broad view is needed that requires access to design intent and the processes and behavior of many people at many companies.

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[2] In fact, a crude economic argument can be made that the amount of money involved in car and commercial aircraft production is about the same, approximately $2.5 billion of final sales per year per assembly line. That is, a typical car assembly line makes 125,000 units per year at $20,000 retail price per car; Boeing's annual sales of $25 billion divided by 5 major assembly lines yields $2.5 billion per line per year.

[3] An expert in this area at a car company said "First you have to make the plan, and then you have to ride herd on the plan."

A knowledgeable person at one of our auto partner companies said "We design parts, we don't design assemblies." This company actually does much better than that, but the point is clear and we found symptoms of it at most of our partner companies. We call it being "part-centric." Part-centric design focuses, as the name implies, on detailed design of individual parts and leaves til later, if ever, the problem of deciding how the parts are to go together. This approach has been encouraged unintentionally by the rising ability of three dimensional computer-aided design (3D CAD) to enable this phase of design without corresponding support for design of assemblies. We frequently encountered the opinion that "We will use 3D CAD and so we won't have any problems during assembly." Or "I thought 3D CAD had eliminated shims." Or "The product just snaps together."

The fact is that 3D CAD can eliminate gross errors in the design (the equivalent of mean shifts in manufacturing) but it cannot eliminate manufacturing and assembly variation. Electronic parts are always the right size, so electronic pre-assembly always works. As so many companies have found out, eliminating variation requires different methods and important organizational and cultural shifts.

All these considerations justify our studying assemblies as indicators of how the product development process and supply chain work in general and how to make improvements that are effective at the system level.

1.2 Methodology

1.2.1 Case studies and field sites

The research methodology followed in this project was to form relationships with a number of companies in the auto and aircraft industries, identify design and manufacturing sites, and place students there for extended periods of time, usually every summer and every January. Shorter visits were made in between. In some cases, the students were interns in the MIT Leaders for Manufacturing program, in which case they spent 6 months on site at a host company. Faculty supervisors made repeated visits while the students were on site and kept up communication via electronic mail. Figure 1-2 diagrams the partnerships developed in the two MIT programs while Table 1-1 lists the field projects in more detail. In addition to the major partners listed in the diagram, extensive but informal interaction with other automotive companies (notably Chrysler and Toyota) and electronics companies (notably Intel, Compaq, and Dell) also added significantly to our learning.

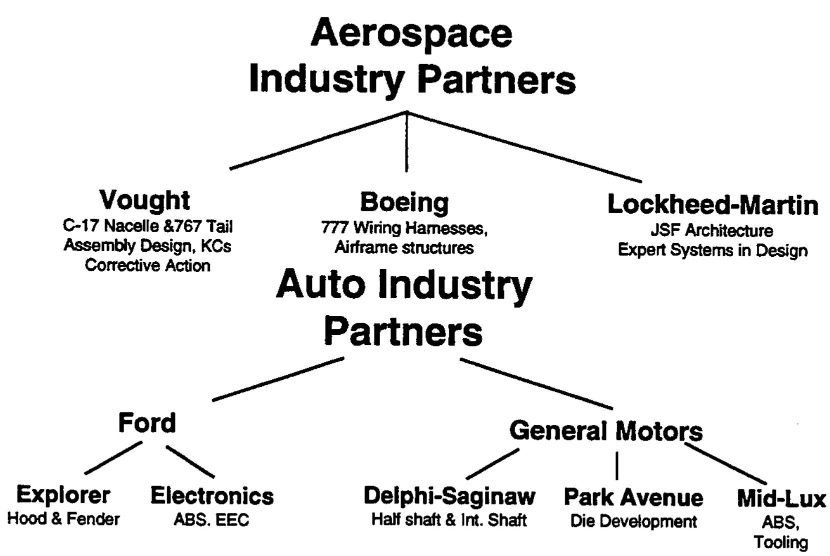

Figure 1-2. Industry Partners and Project Foci

Field Project(s)	Site	Tool developed	Major lessons
Corrective Action in assembly (2)	Ford and Northrop Grumman Vought Center	Contact chains	Need design intent info and systematic CA process to make CA fast
Precision Assembly of 767 Horiz Stabilizer Skin (2)	Northrop Grumman Vought Center	Contact chain, KCs, assembly sequence analysis, VSA, cost analysis	Need process capability data and design intent data to permit rationalized process design
Outsourcing of major aircraft tooling	Boeing	Supply chain and cost analysis	Need cultural and organizational change to enable win-win customer-supplier relationships
KC case studies and maturity model	22 companies	KC Maturity model	KC maturity is low
Org learning for precision assembly	Northrop-Grumman Vought Center	Design Structure Matrix	Precision assembly requires diagnostic skills rather than manual skills
Modeling of assembly layouts for top-down design and process planning (3)	Ford, Northrop Grumman Vought Center, Boeing, Kawasaki Heavy Industries	Datum Flow Chain, CAD models of assemblies, tolerance chains	Benefit of simple diagrams that emphasize how KCs are delivered
Identification of integration risk during concept design	Lockheed Martin Ft Worth	Contact Chain, System Producibility Analysis, Chain Metrics Method	Product architecture and integration risk can be estimated using data available during concept design
Clockspeed-based assessment of supply chain evolution	Ford, GM, and various "fast-clockspeed" companies in the electronics industry	Double Helix Model	Supply chain structures oscillate between vertical and horizontal structures
Strategic Supply Chain Design	Ford, GM, Boeing, and various "fast-clockspeed" companies in the electronics industry	Supply Chain mapping and dynamic analysis tools	Outsourcing can pose significant risks if done without careful consideration of supply chain evolution dynamics
Three-Dimensional Concurrent Engineering	Ford, GM, Boeing, and various "fast-clockspeed" companies in the electronics industry	Strategic 3-DCE integration approach and tools	Product architecture and supply chain architecture concepts can anchor the approach to 3-DCE

Table 1-1. Field Research Projects Listed by Site, Tools Used, and Lessons. Each of the tools and many of the projects are described in detail later in this report.

1.2.2 Project Organization

This project was organized around the assumption that information and knowledge have a natural flow in a manufacturing company. This flow starts out with customer requirements leading to design specifications and designs. These designs are prepared for manufacturing, and production is launched. During production ramp-up, problems occur and corrective actions are instituted. Learnings from corrective action and later production are (or should be) recycled back to the design process for subsequent products. This cycle can be likened to the plan-do-check-act cycle attributed to Deming.

In the case of this project, the cycle can be illustrated in Figure 1-3.

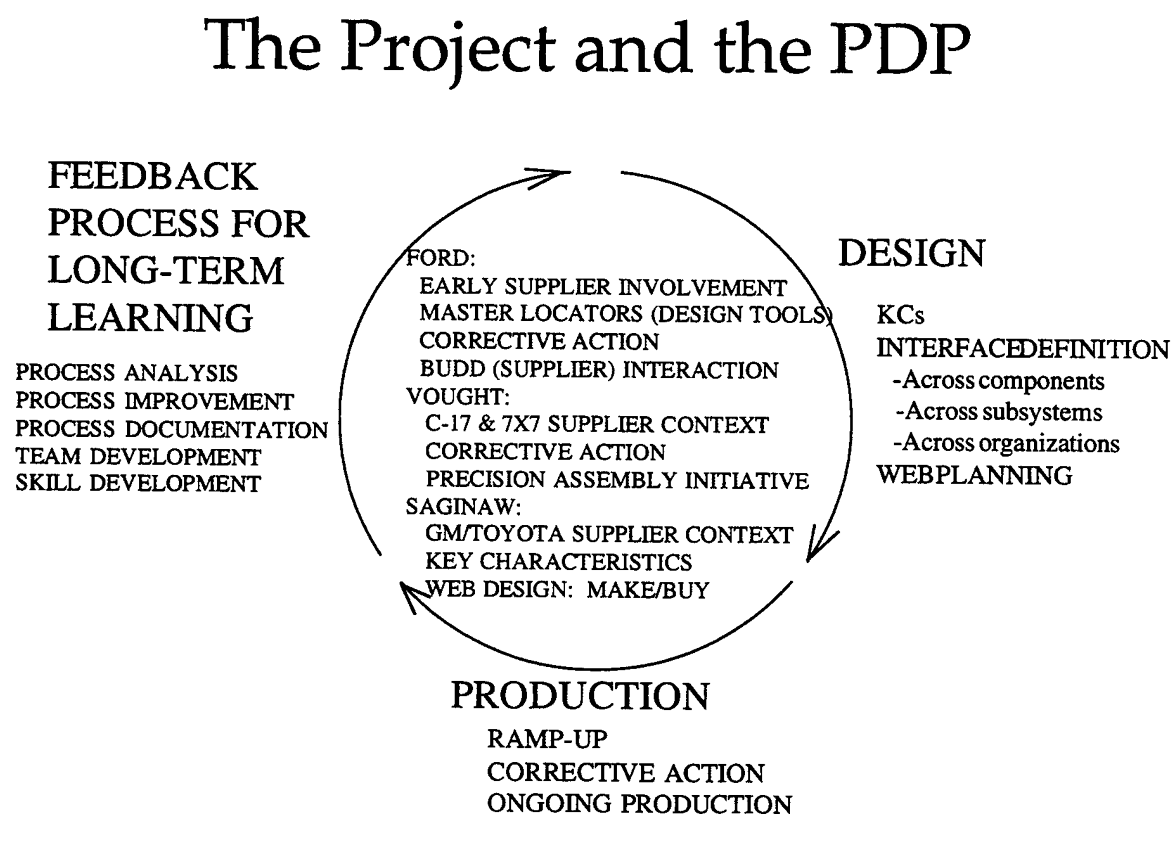

Figure 1-3. Mapping of this Project onto the Product Development Process (PDP) in the Format of Plan-Do-Check-Act. Several example activities within the project are shown, along with the tools and methods used.

1.3 Multiple lenses and tools developed

The research emphasized the need to combine technical, organizational, and managerial issues. In order to do this, we developed a number of "lenses" through which we viewed the problem of procuring complex assemblies from a web of suppliers. The lenses are:

Key Characteristics (KCs) -- A product feature lens that identifies important customer requirements and expresses them in engineering specifications

Web Maps -- A supply network lens that indicates which suppliers are responsible for which elements of the chain of parts and assemblies that deliver a Key Characteristic

Design Structure Matrix (DSM) -- An information flow mapping lens that shows how different tasks and product design team members exchange information

Contact Chains -- A physical product lens that maps which parts participate in delivering a Key Characteristic

Activity Cost Chains -- A cost/DFM lens that traces costs to the activities necessary to deliver the KC

Feature-based Design for Assembly -- A physical model lens that permits assemblies to be described in CAD

Each of these lenses emphasizes a different aspect of the problem. The relationship of these tools to the basic problems of product development is shown in Figure 1-3.

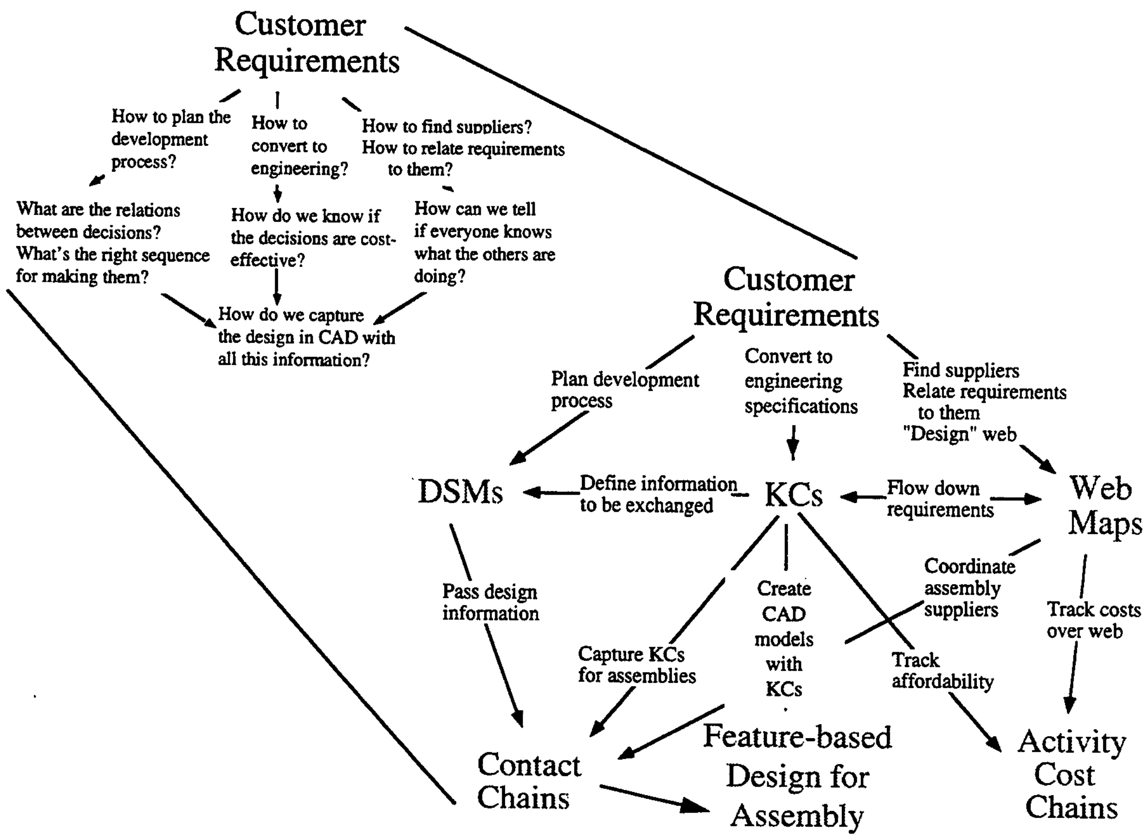

Figure 1-4. Tools Developed in this Project and Their Relationship to Basic Questions in Product Development

The upper left of Figure 1-4 shows the challenges faced by product developers while the lower right shows the tools developed during this research for addressing them. Product development begins with identifying customer requirements and planning a response in three domains: performance (in the middle of the figure), product development planning (at the left), and identification of partners and suppliers (at the right). Across the middle are three coordination issues that highlight the problem of relating steps in the development process, decisions in the design process, and communication in the supply chain. At the bottom is the question of implementing better product development in new computer tools.

At the lower right of Figure 1-4 is the same diagram populated with names of tools or methods developed or adopted and improved during this research. At the left is the DSM, or Design Structure Matrix, a method of recording the fact that different steps or participants in the process exchange information either in a feed forward or a feedback way. Few people have a high level view of the design process they are involved in, and the DSM has proven valuable in providing that view and enabling re-engineering of processes to streamline information exchange. In the middle are Key Characteristics (KCs) that capture customer requirements that could be at risk due to variation. Identification and flowdown of KCs is a newly emerging way to systematically distribute requirements to subassemblies, suppliers, and individual parts so that top-level quality is obtained. Web maps are diagrams of suppliers and what items they make. (See Figure 1-4) Contact chains illustrate which parts touch each other in the process of combining to deliver a KC. Such maps are invaluable for designing assemblies so that they in fact succeed in delivering KCs and for helping the diagnostic process when there are problems on the assembly line. The most informative web maps have the contact chain superimposed on them so that everyone can see their role in delivering the KCs. Feature-based design permits CAD systems to capture KCs and contact chains so that quantitative design data necessary for design and analysis are integrated with geometric models. Activity cost chains permit activity-based costing to be applied to contact chains to determine the cost of delivering a KC.

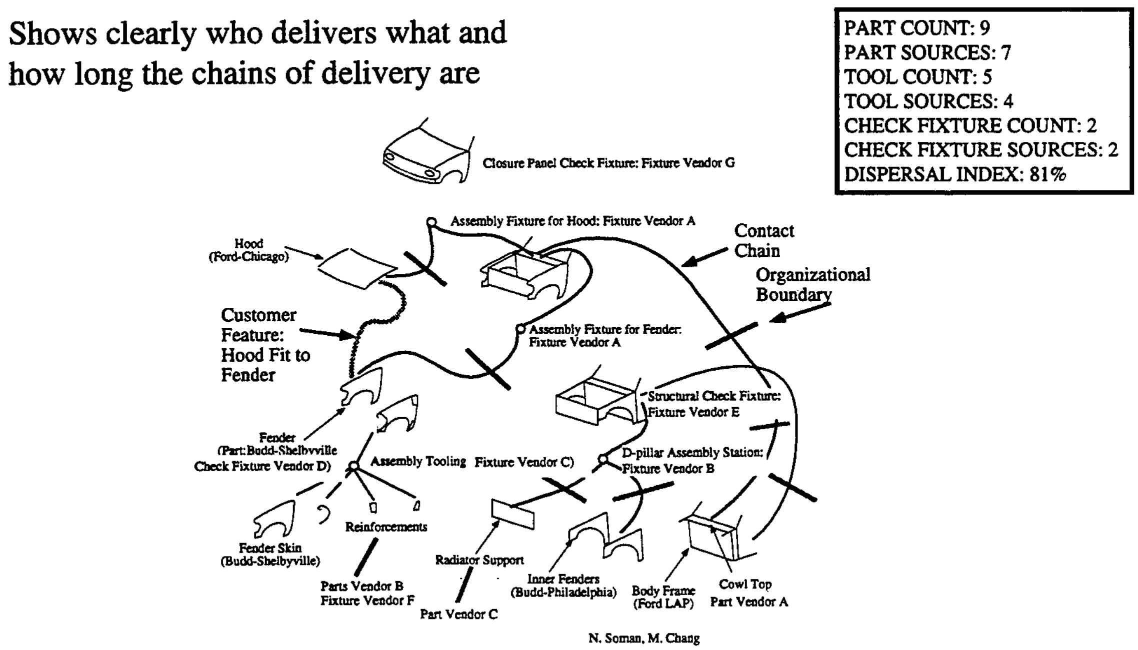

Figure 1-4. A Web Map of an Automobile Front End Customer Requirement. This map diagrams a real product and indicates the high degree of outsourcing involved in both parts and tooling. In a qualitative way, this diagram superimposes a tolerance chain onto the supply chain. Without maps like this, line workers have a hard time diagnosing assembly problems.

1.3.1 Specific tools developed or used: DSM, DFC, SPA

1.3.1.1 The Design Structure Matrix

A design structure matrix [Steward], [Eppinger et al] is a square array that permits diagramming of task, information, design parameter, or people interactions. Unlike the hierarchical IDEF models, DSMs are flat. Basic relationships and clusters of tasks (similar to intensive clusters of transactions) show up vividly on a DSM and can be seen easily by almost anyone regardless of their technical background. Figure 1-6 shows a simple DSM and defines basic terms. Figure 1-7 illustrates canonical patterns of task interactions that are made visible by a DSM.

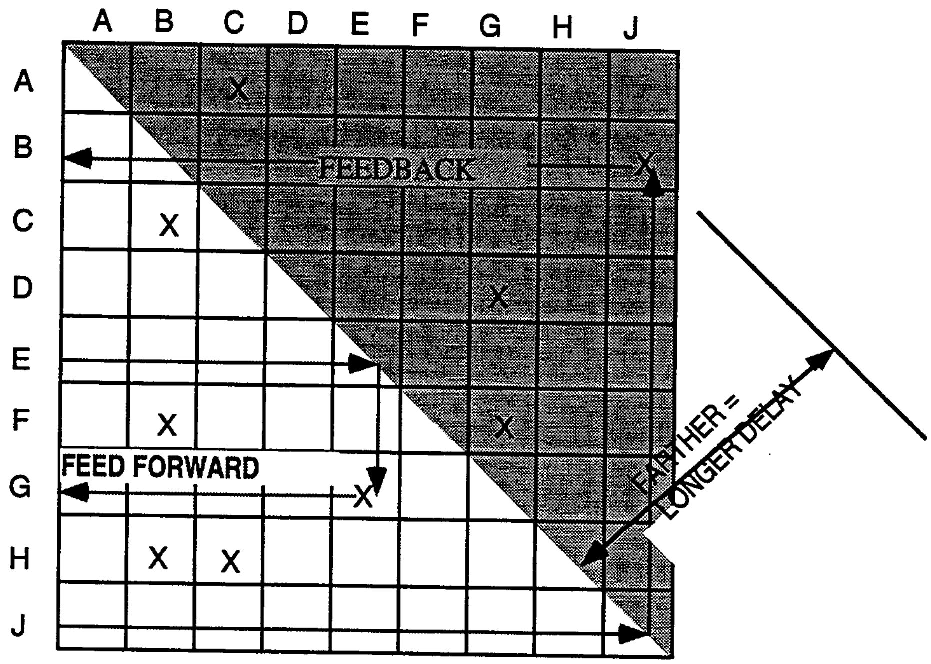

Figure 1-6. Basic Design Structure Matrix. Tasks are listed across the top and down the side in the nominal sequence of execution. An X in a cell means that the task along the top passes information to the task down the side (E to G, or J to B). Xs below the diagonal pass information forward while Xs above pass it back. Thus the DSM can capture structural iteration and repetition of tasks. Sometimes it is possible to rearrange or split tasks in order to make information flow more efficient, eliminate iteration, or shorten feedback loops.

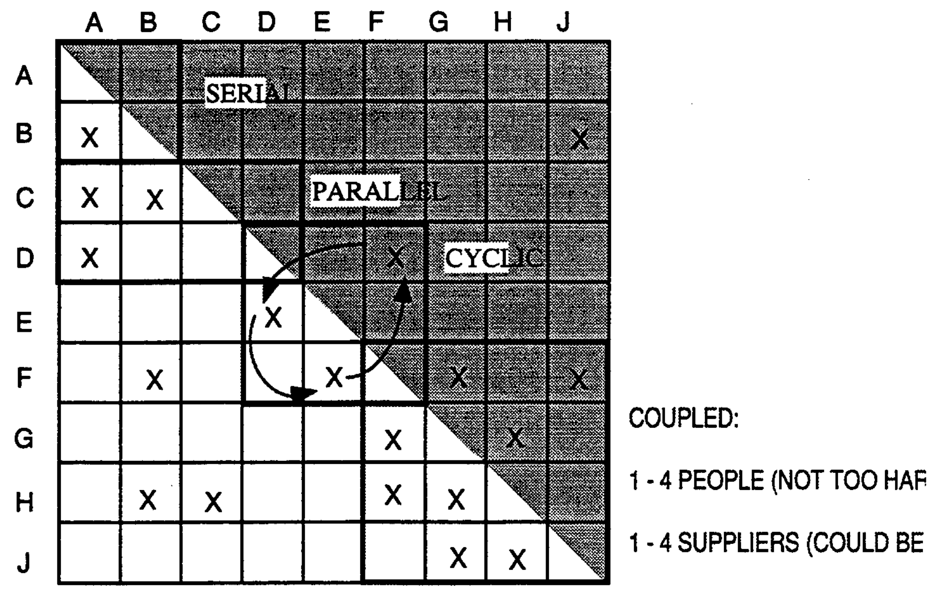

Figure 1-7. A DSM Can Represent Four Classic Kinds of Task Interactions: Serial, parallel, cyclic or iterative, and coupled.

DSMs have been used for the following purposes in this research and other projects:

present as-is processes to their participants in order to encourage improvements

verify that specific KCs are being designed for delivery by a coherent process

identify bottlenecks in processes and focus management attention on them

identify interactions between parameters needed or measured during assembly and the upstream workstations where those parameters were set

show who should participate in team meetings intended to resolve certain issues or design specific items that deliver a particular KC

advise architects and facility designers who are arranging space for design teams so that communication is easy for people whose activities are closely related

provide traceability from decisions to supporting analyses or earlier decisions to aid design rationale and design reviews

1.3.1.2 The Datum Flow Chain

A datum flow chain (DFC) is a directed acyclic graph that indicates how parts locate each other in space. It has one root, which is the primary datum (in a base part or a fixture) and contains nodes that represent parts or fixtures and arcs that represent passing of dimensional location and constraint from part to part or fixture to part. A DFC contains the logic of the assembly layout and captures the designer's intent for how one or more KCs will be delivered. When fixture-based assembly methods are used, the DFC typically contains the fixtures. A DFC contains information about which degrees of freedom on a part are constrained by one or more other parts. At each interface between parts one can assign an assembly feature that constrains those degrees of freedom. One can also apply tolerances to each arc and thus analyze the robustness of KC delivery. Thus the DFC combines three kinds of design intent: dimensional location strategy, constraint, and tolerance analysis.

1.3.1.3 The System Producibility Analysis Method

The System Producibility Analysis method (SPA) utilizes a qualitative version of the DFC to permit members of an IPT with diverse backgrounds to discuss alternate ways of achieving KCs during concept design. Concept design is the most fertile and formative phase of the product development process. During this stage, customer requirements are converted into specific functional requirements, which are in turn converted into trial physical embodiments. These embodiments comprise the architecture of the product, that is, the definition of the physical elements and the interrelations between them. In different physical concepts, these relationships may be more or less complex as well as more or less capable of delivering the required performance and more or less easy to assemble and test. Each of the main participants in the IPT (performance designers, producibility engineers, and outsourcing strategists) will evaluate each concept differently according to their needs. The SPA method allows them to diagram KC deliverability systematically using a set of symbols that they all can understand, and allows them to evaluate each concept to estimate its degree of integration risk: the likelihood that the constituent parts and systems, even when made properly, will not function together as intended.

1.4 Summary of Results, Findings and Recommendations of the Auto and Aero projects combined

1.4.1 Importance of the data provided by the design process

Advanced companies have realized that the early stages of product development are the most creative and important because they set the conditions for later phases and for production. Concurrent engineering or integrated product teams (IPTs) consist of widely different constituencies with different motivations, concerns, reward structures, and languages. The most prominent during actual design are those representing performance, producibility, and strategy (technology for product and process plus identification of key suppliers and partners). Each of these constituencies provides rationale for important decisions regarding design concepts, outsourcing, and production methods. These decisions and the rationale behind them are needed by later participants as they weigh tradeoffs or diagnose problems. Today's design processes and supporting computer tools are inadequate to capture and structure all the information and make it accessible.

1.4.2 Importance of a top-down approach

A top-down approach to product development starts with customer requirements for performance and cost, and proceeds systematically to identify alternate concepts and physical realizations. Experienced designers apply known techniques in a pragmatic way, responding to schedule and competitive pressures. In addition, designers in the car industry are increasingly reusing past parts or assemblies in order to save time or money. In the academic community a set of top-down theories has evolved that appears adequate for design of simple products but may fall short when faced with really complex things like cars and aircraft. Top-down design theory tends to recommend a divide and conquer approach that leads to highly modular products. Aircraft and cars often contain non-modular elements that combine many functions in one part or subsystem in order to optimize weight, energy, or space. Outsourced items must be self-contained modules for a number of practical reasons. Thus it is rare that a design can be purely top-down, purely modular, or totally optimized. A new kind of top-down approach is needed that preserves the ability to meet customer needs and determine the requirements of lower level systems in a rational way.

1.4.3 Combination of technical and business issues

"Our problems are non-technical." We heard this numerous times during this research. What keeps people from adopting good new techniques or tools? Why does upper management think things are going fine while the people on the floor know better? Why do suppliers appear able to deliver quality but the prime contractor has no way of evaluating the promises? Adding more CAD or CMMs will not solve these problems. People need a better understanding of why they are doing what they are doing and why the things they are building were designed as they were. People need to understand the business case behind the technical tools and know where and why money will be saved. Line workers at one station need to know the problems and needs of the people at the next station down the line who are their customers. The more people know about "why," the better they will be able to do their jobs and help others do theirs.

1.4.4 A new perspective on supply chain design and management

Today's products and processes are so complex that one company can hardly afford to know how to do every step or make every part. Henry Ford vertically integrated his company because there were so few competent suppliers. Today suppliers often have better products or processes than top tier firms, and their strength may be growing in some areas. Thus top tier firms are increasingly dependent either for capacity to meet their needs or for the knowledge to make key parts or subsystems. Supply chain *management* (logistics of delivery) is giving way to supply chain *design*, a conscious effort to structure the dependencies so that the product is designed from the beginning by a partnership of companies each of which knows its role in delivering the KCs. Companies need to be very careful during product development to identify each contact chain by which each KC will be delivered and controlled, then to hand out responsibility for each link in the chain to competent suppliers, and finally to monitor the construction and maintenance of each chain.

1.4.5 The need for design tools that emphasize chains

Today's CAD is so good at permitting design of individual parts and vividly displaying them that designers skip over the integrative and definitional stages of design. Designs thus lack an integrative strategy that can be passed on to individual designers and suppliers of parts and to the assemblers. A top-down approach needs to emphasize the logic of the design before the geometric details are approached. Today's CAD can show parts in the correct relative location and can find gross errors that cause interferences. They can also identify when parts are fully constrained. However, they cannot locate parts by joining them at predetermined assembly points, and they cannot create links of such points abstractly in the form of chains such as the DFC. The whole idea of interfaces and relationships needs to be made a top-level definitional tool in CAD systems.

1.4.6 The need for tools that emphasize communicative power

Because members of IPTs come from widely differing disciplines and backgrounds, any new tools to aid the design process need to have high communicative power. It may even be necessary to sacrifice quantitative detail or accuracy for the time being in favor of wide understandability. During early design, wide ranging understanding is more important and in any event there is often too little detail to permit quantitative analysis anyway. Several of the methods and tools developed or used in this research emphasize communicative power over quantitative accuracy.

1.4.7 The need to augment concept design to focus on product architecture

Concept design is the phase where a product's functional requirements are identified and converted into a plausible set of physical elements in a plausible physical arrangement. This arrangement is called the product's architecture. Architectures can be *integral* or *modular*, depending on how independently the physical elements act in delivering the product's functions. Modularity carries several advantages, including simplicity during design and manufacture. In many products, especially complex ones, there is some advantage to integrality, including efficiency in some dimensions of performance. Most complex products therfore contain a mix of integrality and modularity. Integrality can appear in various ways: sets of parts, sets of people, and sets of organizations whose characteristics or activities affect each other in the process of delivering their required performance.

Along with integrality comes what we call "integration risk," the risk that apparently properly design and made elements will not function as desired when assembled into a system. Integration risk spawns cost and schedule risk. A design team needs a way to both establish the architecture during concept design and to assess each concept's degree of integration risk. Often the team establishes the architecture as a byproduct of other decisions and exits concept design without knowing how much integration risk is built in. This risk then attacks the product later in the design process or during production ramp-up. In this project, tools were developed to help IPTs to focus on architecture options and assessment of integration risk during concept design.

1.4.8 A vision for Chain-driven product development

In modern products, it is increasingly true that quality is delivered by systems or sets of parts working together. Such systems display an integral character. Examples include ride quality in cars and fuel efficiency in aircraft. Design processes therefore need to focus first on identifying the chains of participants (parts, people, companies) in each of these quality delivery systems. We need better design methods, data models, and customer-supplier practices to encourage product development that focuses on these chains. In a true chain-driven product development process, there will be a chief systems engineer to whom will report chief system engineers for performance, producibility, and supply chain design and management. Each of these three will have colleagues who are members in equal standing on IPTs. A simplified organizational chart of chain-driven product development is given in Figure 1-5.

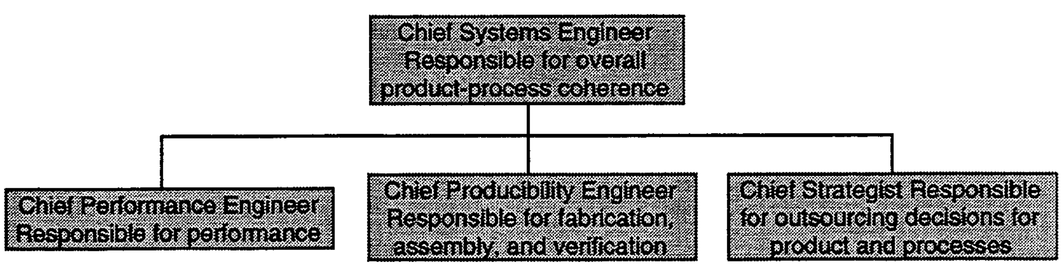

Figure 1-5. Organization Chart for Chain-Driven Product Development

1.5 Section summary

This section of the report presented the context for the research, the web of companies that work together to create complex products, and focused the research on complex mechanical assemblies. The research methodology was explained, the main tools and methods developed were listed, and the main findings were presented. The sections that follow expand on these topics, leading to sections that present details on some of the specific tools and methods developed, with examples of their use.

2.

The Web-Driven Product Development Environment

2.1 The Product Development Process Seen from the Point of View of Assembly

To set the stage for the technical results presented in Sections 3 - 10, we need to describe the environment in which complex products are designed and procured. Since the focus of this research is assemblies, we first describe in Section 2.1 the integrative capability of assemblies and their usefulness as models for how design and procurement of other complex items could be managed. The second topic, treated in Section 2.2, is outsourcing, the act of contracting with other companies to make or even design some of the parts or subassemblies. Depending on the characteristics of these assemblies and the degree of design and manufacturing knowledge retained by the prime contractor, we indicate four different kinds of outsourcing situations which have different promise of success. A summary of a case study from an industrial partner (Section 2.3) is used to illustrate how different companies approach outsourcing and the lessons that can be learned. The third topic, treated in Section 2.4, is the specific management of dimensions and tolerances in the parts and subassemblies, whether they are outsourced or not. The story of Ford Motor Company's Dimensional Control Group is used to illustrate the requirements of this activity.

Our research leads us to conclude that design and management of the supply chain for complex assemblies must be handled very carefully. In particular, the contact chain that traces delivery of Key Characteristics among sets of parts must be mapped onto the supply chain itself, as illustrated in Figure 1-4, so that all interfaces between parts and companies are recognized in advance and fully documented.

2.1.1 Assembly as an integrator

Products are increasingly being made by a "web" of companies, as illustrated in Figure 1-1. The example in Figure 1-4 indicates that some things are outsourced almost down to the last part and fixture. The "moment of truth" occurs at the top of the web when all the outsourced items must come back together and work together. Mechanical assemblies provide excellent examples of the challenges faced by companies in such a process. Integration errors in assemblies are palpable: you can feel them or see them directly. Customers notice them. Product function may be hurt in obvious ways. Thus assemblies and assembly processes are coupled directly to fabrication, vendor control, quality, and market acceptance.

For these reasons, assembly can be used as the focusing issue for achieving integration in web-driven product development. Assembly is the first time that parts are put together. Before that point they are designed, made, handled, and inspected separately. During and after assembly they are joined, handled, inspected, and must work together. Thus assembly is inherently integrative. One can look back upstream to the design and production process from the point of assembly and see clearly the need to carry out these upstream processes in as integrated a way as possible.

In this section of the report, we will look at two important aspects of web-driven product development that affect final assembly quality: strategic aspects of outsourcing and development of dimensional control plans that include suppliers. To support this discussion and also later discussions of research results, we need to review the concept of integral and modular designs.

2.1.2 Integral and modular designs

When a product is designed, one of the first steps is to list the functions the product must perform and then conceive of various physical embodiments that have a chance of delivering the functions. The conversion of functional requirements into physical elements involves creating the product's "architecture." Product architecture is the scheme by which the functional elements of the product are arranged into physical chunks and by which the chunks interact. [Ulrich and Eppinger] Two main kinds of architecture are integral and modular. In an integral architecture, parts may contribute to many functions, and functions may be delivered by many parts. These parts are likely to have many complex interactions with each other. In a modular product, each part is likely to have one function, functions are likely to be delivered by one or a few parts, and parts are likely to have few interactions with each other. Most products contain a mix of integral and modular features.[4] Figure 2-1 shows integral and modular car bodies.

Integral and modular architectures each have their advantages and disadvantages. Integral is often used when the designers want efficiency in terms of weight, energy consumption, or space occupancy, because interfaces between modules usually require additional material. Integral is often unavoidable, as discussed in Section 5, because product elements have complex interactions even though they appear to be separate. Mechanical assemblies are a prime example of this hidden integrality. Modular designs are appealing because they separate functions as well as the people and organizations responsible for them into manageable chunks that can operate somewhat independently. While the principles of system engineering and product design theory aim for modularity as an ideal, most real products are a mix of integral and modular characteristics and thus require care during design to ensure that the integral portions are accounted for ahead of time.

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[4] In a bicycle, parts like the wheels, pedals, and chain are modular, because they do one primary thing for one functional purpose, but the frame is integral since it serves many functions: bracing the wheels, anchoring the steering mechanism, and supporting the rider, among others.

This point is relevant to the design and function of assemblies. Modular assemblies will get much of their quality from the assembly process itself because each part has only a few features, whereas integral assemblies will get much of their quality from their fabrication processes because each part has many features. In the limit of 100% integrality, such as in large composite aircraft parts, basically all of the quality is attained during fabrication (cutting, layup and cure). However, it is a mistake to assume that just because an assembly has many parts, it is modular. In fact, the parts may have many complex dimensional relationships with each other, all of which must be set up correctly during fabrication and assembly in order that final quality is achieved. In Section 2.2, the success or failure of outsourcing is related to integrality and modularity. In Section 5, we introduce the concept of "integration risk" and show how it can be predicted qualitatively during concept design by carefully mapping the architecture using contact chains. Sources of risk that this method can identify include managerial, organizational, and technical, including issues raised by outsourcing.

2.2 Extent of Outsourcing and Its Effects

Outsourcing decisions are often made on a short term basis by comparing the cost of making an item with the cost of buying it. Usually the costs being compared fail to include many components, such as managing the supplier. As technology advances, many companies find that they cannot be good at everything, and thus find it necessary to outsource regardless of cost. Other companies outsource for business or even political reasons, such as mandated subcontracting in defense contracts or "offsets" used by commercial aircraft builders to obtain foreign sales.

During this research we had a chance to think about outsourcing [Fine and Whitney] and identified the following issues:

Outsourcing can create integration risk and management problems if integral items are split up with part going to one supplier and part to another (or part being kept in-house)

Outsourcing can create dangerous dependency for critical product or process technologies

Only certain combinations of type of dependency and degree of modularity are appropriate for outsourcing; others can cause serious managerial or strategic problems

Companies that outsource face the problem of monitoring suppliers who may have skills that the outsourcing company no longer has; this makes it difficult to formulate competent specifications for the outsourced item and to determine if the supplier has met the specification

2.2.1 Different kinds of dependency

Dependency on a supplier can be trivial or total. We categorize dependency into two main types:

- dependent for capacity, and

- dependent for knowledge

Dependency for capacity simply means that a company needs more of an item than it can conveniently provide. It knows how to make the item and finds a second source to augment its needs. Dependency for knowledge is totally different, because the company no longer knows how to make the item and must obtain it outside. In the spirit of agility, many companies voluntarily opt for being dependent for knowledge. One can wonder at the long term wisdom of such a policy.

2.2.2 Different kinds of oursourcability

The easiest things to outsource are those that are easily separated from the rest of the product physically and functionally. Completely modular products can in principle be outsourced down to the last part. Simple circuit boards are an example. Not only can a properly designed board be outsourced, but the common circuit elements on the board can be further outsourced. It is more difficult to outsource aircraft fuselage panels, however. These are large and join many other panels in many places. A large number of different dimensional relationships must be satisfied at the same time in order to create a strong and attractive assembly.

2.2.3 The dependency-outsourcability matrix

In Figure 2-2 we have combined the extreme possibilities of integral and modular (decomposable) with the two kinds of dependency to create four situations. Each situation is more or less desirable for a company considering outsourcing.

	DEPENDENT FOR KNOWLEDGE	DEPENDENT FOR CAPACITY
OUTSOURCED ITEM IS DECOMPOSABLE	**A POTENTIAL OUTSOURCING TRAP** YOUR PARTNERS COULD SUPPLANT YOU. THEY HAVE AS MUCH OR MORE KNOWLEDGE AND CAN OBTAIN THE SAME ELEMENTS YOU CAN.	**BEST OUTSOURCING OPPORTUNITY** YOU UNDERSTAND IT, YOU CAN PLUG IT INTO YOUR PROCESS OR PRODUCT, AND IT PROBABLY CAN BE OBTAINED FROM SEVERAL SOURCES. IT PROBABLY DOES NOT REPRESENT COMPETITIVE ADVANTAGE IN AND OF ITSELF. BUYING IT MEANS YOU SAVE ATTENTION TO PUT INTO AREAS WHERE YOU HAVE COMPETITIVE ADVANTAGE, SUCH AS INTEGRATING OTHER THINGS
OUTSOURCED ITEM IS INTEGRAL	**WORST OUTSOURCING SITUATION** YOU DON'T UNDERSTAND WHAT YOU ARE BUYING OR HOW TO INTEGRATE IT. THE RESULT COULD BE FAILURE SINCE YOU WILL SPEND SO MUCH TIME ON REWORK OR RETHINKING.	**CAN LIVE WITH OUTSOURCING** YOU KNOW HOW TO INTEGRATE THE ITEM SO YOU MAY RETAIN COMPETITIVE ADVANTAGE EVEN IF OTHERS HAVE ACCESS TO THE SAME ITEM.

Figure 2-2. The Matrix of Dependency and Outsourcability.

In the upper right is the best situation. Here, a company understands the item to be outsourced, and it is easily defined by simple specifications of a few interfaces. It is easy to tell if the supplier has done a proper job. By contrast, the situation at the lower left is the most dangerous. Here the company is totally dependent and may not have enough skill to manage the multiple interfaces that an integral item presents, especially when it no longer knows how to make that item and may have created an imperfect specification as a result. An imperfect spec will generate integration problems of its own, making the final assembly even more difficult.

2.3 Mechanical Assemblies as Indicators of Supply Chain Performance

In his study of "black box parts," Fujimoto found that Japanese car manufacturers gradually converted outsourced modular parts like steering wheels from build-to-print (so called white box) to build-to-spec (black box) over a period of 20 years by gradually improving the capabilities of the suppliers. However, parts like rubber door seals never advanced beyond the white box category even after 20 years. [Fujimoto] This example indicates that the distinction between integral and modular is important in defining the limits of outsourcability: door seals depend for their performance on the dimensions of many other parts and thus must be controlled in detail by the prime. Steering wheels attach with a bolt and an electric plug (until the era of air bags) and are relatively easy to decompose, describe in a spec, and outsource completely.

A more striking example is provided by research work in this project at General Motors Delphi Saginaw Division. MIT staff and students performed a detailed analysis of how one product, a half shaft for front wheel drive cars, is made. Delphi is one of the world's leaders in half shaft design and manufacture, and its customers include most of the world's car companies. Figure 2-3 shows a half shaft. These items transmit large amounts of power and are critical safety items. Their flexible joints must be made extremely carefully with close clearances and tight tolerances.

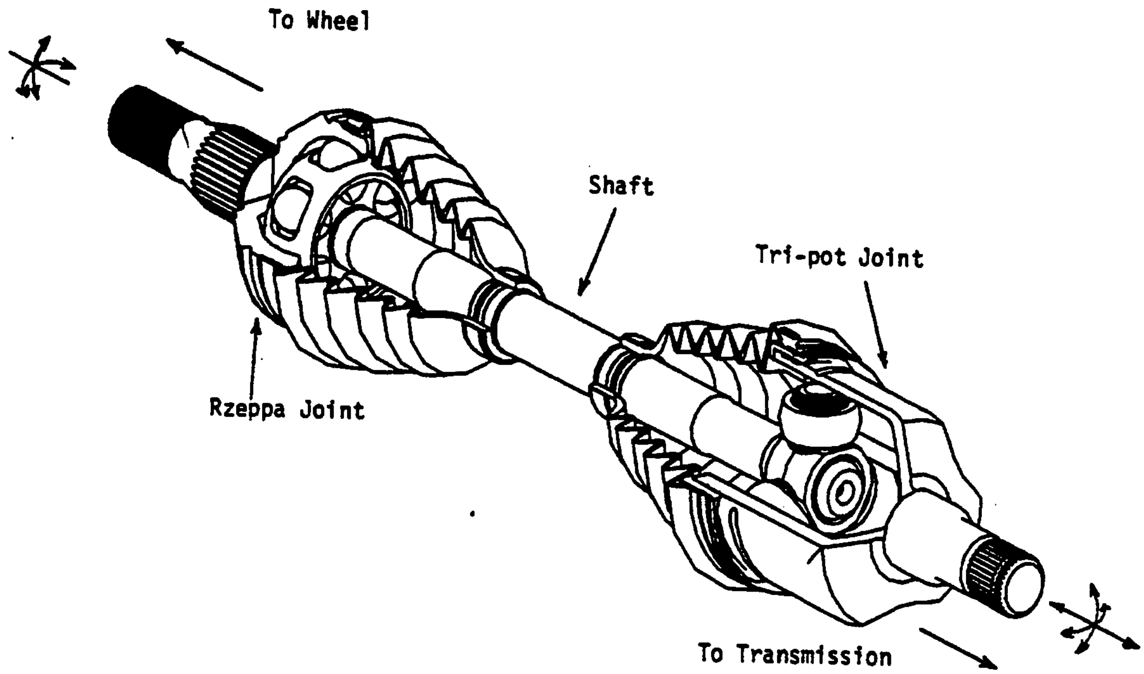

Figure 2-3. A Typical Automotive Half Shaft

Our research showed that different car companies specify their half shafts to Delphi rather differently. Some give minimal engineering specifications, such as length and maximum torque. Toyota, however, provides detailed specifications, including a design verification test to determine the first mode transverse vibration frequency. Such a specification has nothing to do with torque carrying capacity, but rather with noise, vibration, and harshness (NVH). Clearly, Toyota considers the half shaft not merely a torque carrier but as a member of the NVH system. The half shaft thus is not a module but an integral item. Figure 2-4 shows the half shaft as a member of the NVH system.

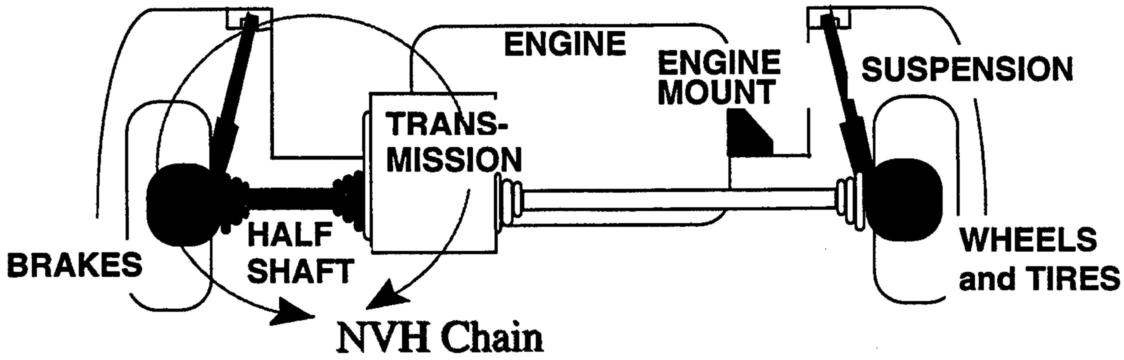

Figure 2-4. Illustrating the Role of the Half Shaft in the NVH System. The system includes engine and mounts, transmission, half shaft, wheels and tires, suspension, and body.

Why then does Toyota feel comfortable outsourcing it? MIT researchers asked Delphi engineers if Toyota goes so far in its specifications as to dictate tolerances. "They would never dream of telling us what tolerances to use. But, if we begin to fail the qualification tests, then they start to get 'helpful.' They are the best in the world and they want us to be, too. They gently nudge us toward the design they knew all along we should have used."[5] It turns out that Toyota makes some of its own half shafts. This indicates that Toyota is dependent for capacity and this explains why it can comfortably outsource an item it obviously considers integral.

2.4 Description of Ford's Dimensional Control Program

The body parts of cars provide a useful illustration of management of dimensions. These parts are complex and difficult to make. Customers pay careful attention to how they fit and whether they permit water leaks or wind noise. Since around 1990 US car firms have greatly improved their control of assembly dimensions, flowing down those dimensions to the parts. Prior to this time it appears that the parts were designed individually without a lot of consideration for how they would be assembled. Assembly process design was considered to be a job for tooling engineers and was addressed much later in the design process.

According to a case study by MIT [Lee], Ford began to pay closer attention to dimensional control after the famous Toyota television commercial that showed a ball bearing rolling along a hood-fender gap. It required the authority and initiative of a Vice President to start the process. At first it was thought that the solution lay in coordinating the calibration of all gages and fixtures, but one employee in the body tooling department determined that the solution lay in a top-down design process that assigned dimensions, tolerances, and "locators" systematically.

Locators are features on the parts by which they attach to the fixtures or other parts. Starting with methods and terminology borrowed from Mazda, Ford developed a standard set of locator designs and methods for applying them. Figure 2-5 is an example part together with many of the symbols. Ford personnel also contacted McDonnell Douglas personnel and learned advanced methods of calibrating fixtures using theodolites and methods of training and qualifying theodolite operators.

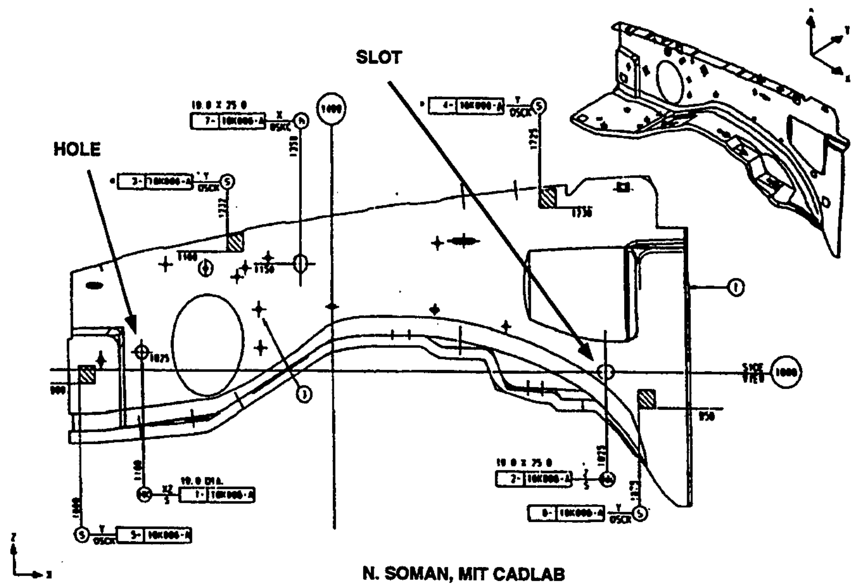

Figure 2-5. Locator Drawing for an Inner Fender Panel. Locators are highlighted with leaders and boxes containing symbols like H (hole) and S(slot).

Ford's locator "vocabulary" includes names of features used for locating, such as hole, slot, and edge, as well as nuances such as "temporary" to indicate that a locator substitution has occurred at one station because the main locator is temporarily obscured, and "transferred" to indicate that datum reference has been permanently transferred because the original locator is permanently obscured.

It is typical that following body design, the development of locator strategy, tooling design, stamping die design, and assembly line design take a year of team effort involving the respective Ford and vendor personnel. A set of books about a foot thick containing drawings like that in Figure 2-5 is the result. This set of books becomes the bible for all subsequent design of individual parts, dies, jigs, assembly fixtures, and check fixtures. Section 7 of this report describes how this information is used on the factory floor to solve assembly problems during production launch. Except for CAD tools adapted to display locators, and the use of VSA (commercial software for tolerance analysis), the design of locator schemes is carried out manually by experts.

Ford personnel understood that the task of improving dimensional control required organizational changes. Ford established the Dimensional Control Group (DCG) in the Body and Assembly Operations (B&AO) department in 19XX. B&AO is responsible for designing sheet metal stamping and assembly lines as well as for contracting for the construction of those lines, supervision of assembly launch, and solution of body assembly problems. By placing the DCG in B&AO, Ford effectively joined dimensional control analysis with control of tooling to achieve dimensional control. Furthermore, Ford provided that the DCG would have design review authority over all body designs. Ford thus achieved good integration of all the elements necessary for managing assembly quality: design, assembly tooling, and assembly line design. Section 7 of this report describes how this information is used for corrective action during production ramp-up.

Our research at aircraft companies indicates that few have achieved similar integration. MIT researchers visited most domestic and foreign manufacturers of large commercial aircraft and did not find evidence of either a company-wide policy that joined tooling and assembly departments into one organization or strongly involved assembly and tooling considerations into an up-front dimensional control plan. At one company, an engineer said "The vendors make the parts using whatever dimensional datums suit their production processes. We have to spend a long time adjusting them to make the assemblies go together." Only at McDonnell Douglas [XX] among aircraft companies is there evidence that good dimensional control occurs.

When Boeing designed the 777, unprecedented efforts were made to involve suppliers and production people in the design process, and there is strong evidence that this paid off handsomely in reduced assembly problems. It is not clear, however, that a systematic top-down process was followed.[6] More recently [Muske], Boeing has studied such a process for an advanced 747 program. Personal contacts with the author indicate that no computer-based methods are currently available to support such a process, which relies instead on experienced people. The methods described in Section 6 of this report may prove helpful.

Ford personnel are also aware of the degree of complexity of assemblies and the need to prioritize the tolerances and KCs. For example, car doors are made of an inner panel and an outer panel. The outer should maintain a constant gap with the surrounding body for appearance purposes. The inner should maintain a constant gap with respect to the same body area for leak and noise purposes. Since inner and outer are joined as a subassembly, there will be errors, and it is impossible to perfectly align the outer and the inner to the body simultaneously. Ford personnel are clear that the inner should be set correctly and the outer allowed to fall as it may, because the customer will notice leaks and noise every day and will be unhappy.

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[6] MIT staff and students studied 777 fuselage final assembly and first tier supplier practices. Portions of the findints appear in [see Aero project report].

Some of our aircraft partners appear to want to achieve every KC to the same level of tolerances. When large structures are joined, many features are supposed to align. Strictly speaking, such an assembly action has only 6 degrees of freedom for making alignment adjustments. Typically, the number of KCs to be achieved during such a mate presents far more than 6. Instead of prioritizing, the assemblers apply force in an attempt to align the other KCs. This can be done up to the point where too much energy is locked into the structure, above which flight load margins are eroded or stress-induced corrosion might occur.

The common approach to such problems is to tighten all the tolerances. In fact the correct approach is to maintain the tolerances on the highest priority KCs and mate them first, using up the first 6 degrees of freedom in the process, while the other KCs should be given looser tolerances consistent with the fact that they must be allowed to fall where they may once the first ones are mated. Otherwise, the assembly will be over-constrained and energy will be stored in it. If this approach does not succeed in permitting important KCs to be achieved to the desired tolerance, then a different assembly sequence must be adopted that mates the degrees of freedom in some different way. Section 6 of this report presents a theory of top-down design of assemblies that describes this idea in detail. Clearly, a different assembly sequence will probably create different modules and subassemblies. The dimensional pros and cons of different modularizations can in fact be studied during concept design, when such ideas are considered and frozen, usually without understanding their effect on assembly. Section 3 of this report presents a theory to address this issue.

Nowhere in the aircraft industry did we observe the level of sophistication that is evident in the car industy. The elements observed at Ford are:

recognition that several key organizations (assembly line design, tooling design, tooling outsourcing management, assembly line installation, and production launch) must report to the same high level manager

recognition that a separate dimensional control group can provide a valuable skill center for anchoring the process

a mandate that dimensional control be part of the design review process for assemblies

development of computer tools for describing locators and provision of computerized libraries of standard locator designs

integration of tolerance analysis software into locator design methods [Ford VSA paper XX]

adoption of KC priorities

realization that management attention and energy must be devoted to maintaining the dimensional control plan once it is adopted so that the many people and suppliers involved do not inadvertantly change something and upset the plan[7]

The car industry has learned a great deal about dimensional control, design of assemblies, KCs, and outsourcing of assemblies. The aircraft industry appears to be learning the same lessons on about a 6 to 8 year time delay. This delay could be shortened if more cross benchmarking and learning between the two industries took place.

2.5 Section summary

This section provided background information on topics that are further developed later in this report. Assemblies were identified as models of integrative design challenges. Integral and modular designs were defined, and the advantages of each were listed. The pitfalls of integral designs were identified in terms of assembly, or integration, risk as well as outsourcing risk.

Two industrial examples of outsourced assemblies were given, half shafts and car bodies, and Ford's methods of managing this process were described. While aircraft companies face similar problems, they appear to lag the car industry in applying best practices.

The following sections of the report describe in detail several research activities and new tools or methods that address the issues raised in this section.

3.

[7] As quoted above: "First you have to make the plan and then you have to ride herd on the plan."

Mathematical and Computer Models of Mechanical Assemblies

This section reviews the state of the art in modeling assemblies in CAD systems. This is an important matter because such models provide the infrastructure for a design process that permits assemblies to be designed systematically. A brief outline of such a systematic method is given in this section and elaborated in Section 6. These assembly models capture KCs quantitatively. They also provide the underlying basis for qualitatively tracing contact chains along supply chains and permitting integration risk to be identified.

3.1 Motivation

It is commonly accepted that some kind of concurrent design or integrated product teams represent the best practice for designing products that can be manufactured effectively. At most companies, this process is carried out by means of meetings between domain experts who provide feedback based on their experience. It was recognized about 10 years ago that early consideration of assembly would help this process by providing an integrative focus. [Nevins and Whitney] However, even today, systematic tools to support this or any other approach are few. Our research has convinced us that assembly remains a promising vehicle for promoting an integrated approach that encompasses performance, quality, and the realities of outsourcing. A computer-based model of assemblies would be very helpful in providing the base for systematic design and evaluation tools to support this approach. The benefits, discussed below, are:

facilitation of a top-down design approach based on the method of KCs

creation of a structure for storing and flowing down KCs

creation of an organized repository for knowledge and information about assembly in general and specific parts and assemblies in a given product that can be used to improve subsequent designs or to help diagnose assembly problems

3.2 State of Implementations of Assembly in Commercial CAD

Until very recently, CAD systems could not represent assemblies as assemblies. The computer power necessary to assemble and display models of many parts at once was lacking. With the advent of solid modeling, a kind of assembly model has come into being. This is often called "electronic preassembly." It permits parts to be located in space in the nominally correct locations in world coordinates (such as buttline, waterline, and station line in aircraft terminology with the origin at or slightly ahead of the front of the aircraft). An interference analysis can then be invoked, mis-sized, mis-located, or mis-shapen parts can be detected, and the errors can be fixed. Since such errors were hard to detect in complex assemblies designed on paper, a great many problems were averted by means of this method.

Current models still fall short in important ways. First, they do not represent the effects of variation. As one engineer put it to us, "Electronic parts always fit because they always hit the nominal dimensions." A false sense of security can result. Second, and more important, such models cannot be constructed from a pre-designed plan for constraint, that is, a strategy indicating which degrees of freedom of a part are controlled by which other part or fixture.[8] Typically, such decisions are the province of tooling designers anyway, but they often come into the process late and must work with the parts as designed. Provision for such decisions earlier, where they belong, would require reorganizing parts of the design process. Third, a consequence of the second, current CAD models do not contain any information about how the parts assemble to each other or even which parts are actually mated as contrasted with merely touching or being near each other. For this reason, there is no built in information to support an assembly tolerance analysis because the information needed to build up a tolerance chain is absent. Tolerance analyses conducted today with commercial software such as VSA must be done by a domain expert who constructs the tolerance chains manually from information provided by designers.

The methods described in Chapter 6 of this report are intended to support creation of a constraint structure for assemblies that provides information on nominal part location as well as the logic of dimensional control and tolerance chains.

3.3 Feature-based Design of Assemblies

Computer-based models of assemblies are at least as old as fundamental robotics research from the 1970s [Simunovic, Popplestone and Ambler]. Each part is given its own origin coordinate frame, and each place (now called an "assembly feature") where it connected to another part is given a coordinate frame as well. The relative locations of these frames are easily calculated. If one specifies that "this place on this part connects to that place on that part," then it is easy to construct a mathematical model of the assembly that locates every part nominally in space relative to its neighbors. This is a true assembly model. An early implementation of this was called "feature-based design for assembly." [De Fazio et al] Figure 4-1 sketches the concept of feature-based design for assembly and compares current world coordinate CAD models of assemblies with a true assembly model.

[8] In fact, there is considerable evidence that designers are not sensitive to the issue of constraint and often design over-constrained assemblies.

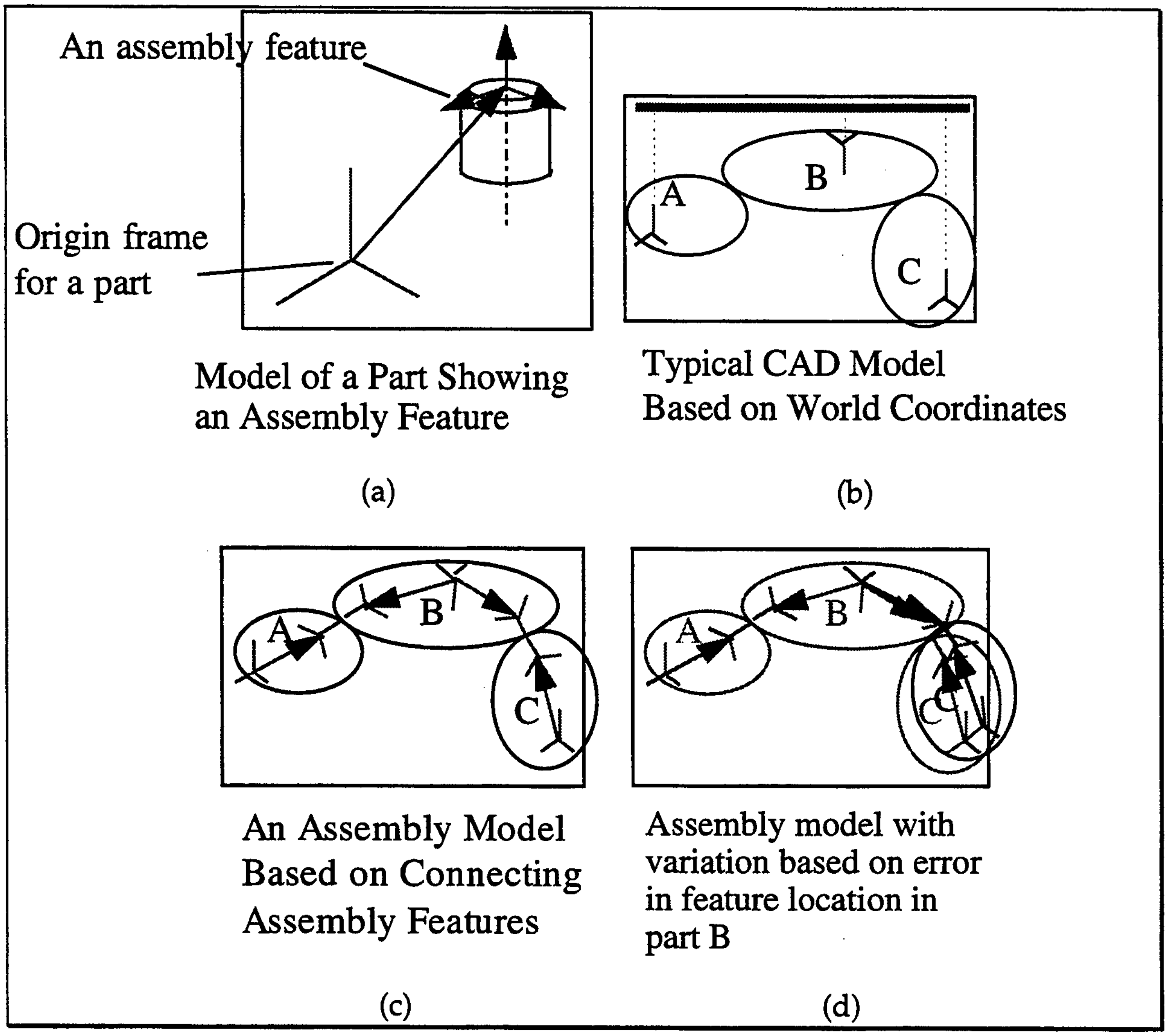

Figure 4-1. World and Relative Assembly Models. (a) An assembly feature, such as a peg, is located relative to the part's origin coordinate system by a coordinate transform represented by the arrow. (b) In a world coordinate model, parts are located in world coordinates so that they are touching each other at the mating features, but the fact that they mate there is not part of the model. (c) In a feature-based assembly model, the features are mated mathematically by joining their coordinate frames. By conducting a series of coordinate transforms, (following the arrows from frame to frame) one can navigate from part to part through the assembly. (d) If there is variation in sizing, positioning, or orienting the features within the parts, the cumulative effects of these variations can be calculated by suitably adjusting the positions and orientations of the frames and tracing the revised locations along the arrows.

3.4 Sketch of a top-down design process for assemblies

Before there was CAD, people who designed on paper used a top-down process for designing mechanical assemblies. The first step was a skeleton layout that showed the basic datums, mating faces, centerlines, and so on. Onto this skeleton the layout person placed outlines of parts. From this layout a rough assembly drawing was made, showing the approximate shape of each part as it lay on a centerline, abutted a datum or mating surface, or abutted another part. Then a detailer drew each part in detail and provided dimensions and tolerances. Finally, a checker rebuilt the assembly drawing using the detail drawings and their dimensions, and checked to see if everything fit. The career ladder for a designer ran from detailer to assembler to layout to checker.

The advent of wireframe CAD spelled the end of this process, focusing programming facilities on the detail phase. People with checking and layout skills are now few. Only recently have CAD systems been able to do some checking by means of interference analysis. When layout people and their skill were lost, design of assemblies became a bottom-up process in which parts were detailed and then fitted together. Tolerances are attached only to parts, and tolerance analysis is largely manual or is done with additional software that often requires domain experts and some translation of data.

It is necessary to restore the ability to create top-down design of assemblies so that KC delivery can be guaranteed and assembly information can be captured and used for tolerancing and corrective action in the factory. Such a process begins with the specification of function and one or more physical concepts. Key performance parameters are obtained from customer requirements lists and converted into KCs (particular dimensions and tolerances on the assembly). A dimensional skeleton should then be proposed with the twin goals of establishing the positional constraints between prospective parts and of controlling the key dimensions.

Parts should be added to this skeleton using the roughest geometry that is sufficient to show how their positions and orientations would be controlled. Control would be established by focusing detail on the locations or features on the parts that act as interfaces to the parts they assemble to. These interfaces are called assembly features. Each kind of feature mate (peg to hole, peg to slotted hole, etc) controls from one to six degrees of freedom of the mating part. A model of the type shown in Figure 4-1 (c) would be built up as each part and its mating features was added. Features could be drawn from a menu for this purpose and attached to the skeleton to show how and where parts eventually will join each other. Once the assembly features have been chosen, checking could be done to see that each part is properly constrained and not over- or under- constrained, unless underconstraint is desired for functional reasons. A tolerance analysis on the skeleton could also be performed at this stage to check that the KCs are under control. Detailed part geometry could be added to the rough parts at any time, once the overall coherence of the dimensional control plan, the mating features, the constraints, and the tolerances had been checked.

This process follows the suggestions of Taguchi, who proposes that design take place in three phases:

system design (here, creation of the dimensional control skeleton)

parameter design (selection of mating features and checking of constraints)

tolerance design (error analysis of the skeleton and features)

Taguchi says that too often the first or even the first two steps are skipped or given too little attention, and people try to achieve everything from step three. This usually means tightening tolerances, which is a costly approach. A poorly designed skeleton or unconstrained/overconstrained parts will create a poor assembly which cannot be rescued by tightening the tolerances. In fact, loosening clearances may be needed to reduce over-constraint.

Another way to characterize this approach is by using the methods and vocabulary of system engineering. The process described above consists of defining and managing the interfaces between the parts first, and then detailing the rest of the parts.

3.5 Assembly of Compliant Parts

The PhD thesis of Narendra Soman, which builds on that of Min Ho Chang, both supervised by Prof David Gossard, addresses the assembly of compliant parts. Unlike rigid parts, compliant parts can deform, changing their geometry during the assembly process. The work of Soman and Chang, provided in their respective PhD Theses[9]

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[9] Narendra Soman, "A Model of The Assembly of Compliant Parts," PhD Dissertation, MIT Mechanical Engineering Department, 1996; Min Hi Chang, "Computational Tools for Identifying Potential Assembly Problem Areas and Designing Products, Tooling , and Processes Robust to Variations," PhD Dissertation, MIT Mechanical Engineering Department, 1995;

Industry Clockspeed and the Double Helix

Clockspeed-based benchmarking is a tool for wringing insights from fast-clockspeed organizations--the "fruit flies" of industry. The tool helps managers comprehend the forces driving industry control, which, in turn, enables better forecasting of these forces across a number of industries. Understanding when and how the takeover of an industry can be accomplished by a player who was once "merely a supplier" is a fundamental lesson from clockspeed-based benchmarking. Furthermore, clockspeed-based benchmarking can aid forecasting industry structure and opportunities for control. For example, the "double helix" model illustrates how industries cycle predictably back and forth between horizontal and vertical structures. Furthermore, these dynamics of industry and supply chain structure are inextricably linked to the product architectures that are evolving concurrently. Modular products (such as personal computers) beget modular supply chains and horizontal industry structures. Integral product architectures (such as jet engines) beget integral supply chains and vertical industry structures. The cycling between integral and modular, between horizontal and vertical, is often imperceptible in slow-clockspeed industries, but may be observed readily in faster evolving ones, providing a powerful tool for forecasting supply chain evolution for strategic positioning.

4.1 The Clockspeed Concept and Industry Fruitflies

One of our research objectives was to understand the role of supply chain development as it relates to product and process development. In particular, we wanted to assess the strategic, long-term impact of supply chain choices as well as their tactical effects. However, as we observed automotive and aerospace supply chains, we saw little resolution of strategic outcomes over the timeframes in which we could observe the industries in real time.

When the Nobel prizes were announced for medicine in December 1995 based on research on fruit flies, we had an insight: We decided to try to apply the research approach of biology, to study rapidly-evolving species and apply the findings to slower evolving species. We started thinking in a new direction: Instead of monitoring the supply chains of corporate slowpokes like automotive and aerospace, why not speed things up by studying the industrial equivalents of fruit flies? If biologists could accelerate their research productivity one hundred-fold by studying *Drosophila,* could we speed up our research by finding and studying industrial fruit flies?

We looked at Intel, one of the sponsor companies of MIT's Leaders for Manufacturing program. It seemed that we might use as industrial fruit flies the customers of Intel -- personal computer dynamos such as Compaq and Dell, whose products were outmoded within months of their launch and whose corporate lives seemed at risk on an almost daily basis. So we decided to explore the idea that fruit fly companies might actually be able to serve the same function for a business researcher that the lowly *Drosophila* serves for geneticists. If so, it meant that lessons learned from observing the rapid evolution of supply chains in a Compaq or a Dell could be applied to benefit organizations in other industries.

We began to look at other industries, seeking to understand their various rates of evolution. We came to think of these rates as industry *clockspeeds*. Each industry evolved at a different rate, depending in some way on its product clockspeed, process clockspeed, and organization clockspeed.

The information-entertainment industry, for instance, is one of the fastest-clockspeed fruit flies of the business world. Its products -- motion pictures for example -- can have half-lives measured in hours, if not days. The biggest returns, for instance, often come from launching a successful product during the Christmas season when the number of viewers is greatest and when a movie can make an impression just before members of the Academy of Motion Picture Arts and Sciences nominate films for their annual awardfest.[10] In December, 1997, for example, the major U.S. movie studios and many of the most luminous American directors collectively launched almost $400 million worth of movies on a single Friday evening, with "their fates [to be] a settled issue by Saturday night," according to one commentator.[11]

Process clockspeeds in the information-entertainment industry are similarly breathtaking. We learn almost daily of new processes and services for delivering information content to the home, office, or mobile work station. Organizational dynamics are turbulent as well. Relationships among such media giants as Disney, Viacom, Time Warner, Inc., and Rupert Murdoch's News Corporation are routinely negotiated, signed, sealed, and renegotiated in hardly more time than it takes a fruit fly to become a grandparent.

Somewhat slower, semiconductors have a clockspeed measured in years rather than months. An Intel microprocessor product family such as the Pentium II has a market life of two to four years. As for its process clockspeeds, each time Intel sinks a billion dollars into building yet another microprocessor super-factory, it expects much of that investment to be obsolete in little more than four years. That gives Intel a four-year window to recoup its billion dollars in capital, plus a return on that investment.

Moving at an even slower clockspeed, the automobile companies typically refresh their car and truck models every four to eight years. In the process domain, they expect that a billion dollars invested in an engine or assembly plant will remain vibrant for 20 years or more.

At the slowest end of the clockspeed scale -- up there with the sea turtles and the California redwoods -- are the manufacturers of aircraft. The Boeing Company, for instance, measures its products' clockspeeds in decades. Mega-profits still flow

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[10] Kurt Andersen, "Auteur Gridlock," *The New Yorker*, December 8, 1997, p. 35.

[11] Ibid.

from sales of its venerable 747 jumbo jet 30 years after its launch. The 747s produced in the 1990s rely on the same basic design and the same manufacturing plant that rolled out the first of these aircraft almost three decades ago. Elsewhere in the slow-clockspeed aircraft industry, Lockheed-Martin was working diligently in 1997 to design a warplane that was not expected to go into production before 2008.[12]

4.2 The First Lesson of the Fruit Flies: Beware of "Intel Inside"

Observers often note that some industries -- telecommunications, computers, and the like -- undergo changes with astonishing rapidity, whereas others seem to mosey along at a leisurely pace, scarcely bothered by changes elsewhere in the business environment. This book, however, seeks to examine the experiences of companies in fast-clockspeed industries and draw from them lessons to apply to others, much as biologists learn about human beings from the research they conduct on fruit flies. In short, the insights that the corporate fruit flies offer can be illustrative and useful to *all* companies, even those with medium or slow clockspeeds.

Every student of industrial competition knows the story of one of the most information-rich fruit flies of the late twentieth century -- namely, the computer industry. Specifically, this is the story of the famous -- one might say, infamous -- turning point that occurred when IBM made its fateful decision to outsource its personal computers' microprocessing needs to Intel and its operating system to Microsoft. Back in the early 1980s, when IBM launched its first personal computer (PC), the company pretty much *was* the entire computer industry. IBM had always prided itself on the technologically deep organization that designed and produced its super-sophisticated mainframe products. But the PC presented IBM with a special "three-dimensional" design challenge: The company needed to create a new product, a new process to manufacture it, and a new supply chain to feed that process and distribute the product.

The business and technical design IBM selected was a departure from the company's tradition of doing everything in-house, from product design and prototyping to manufacturing and distribution. To keep costs low and increase speed to market, IBM chose a modular product design, built around major components furnished by suppliers such as Intel and Microsoft.

By 1998, the personal computer had gone through seven microprocessor generations: 8088, 286, 386, 486, Pentium, Pentium-Pro, and Pentium II. Still a powerful, profitable, and influential company by the standards of the computer industry, IBM had nonetheless been far outdistanced by its two hand-picked suppliers, who had taken the lion's share of the profits and industry clout that

[12] Philip Shenon, "Jet Makers Preparing Bids for a Rich Pentagon Prize," *Wall Street Journal,* March 11, 1996, p. 1.

flowed from IBM's standard-setting product. IBM's suppliers also won the allegiance of millions of customers who came to care far more about the supplier's logo -- "Intel Inside" or "Windows 95" -- than about the brand name of the company that assembled the components and shipped the final product. The power in the chain had shifted, as had the financial rewards.

IBM's decision to outsource its PC's microprocessor and operating system determined the contours of the entire industry for years to come. In terms of its effect on IBM, the PC decision represents a powerful cautionary tale, a lesson from the sad experiences of a fruit fly company: When designing your supply chain, whatever your industry, beware of "Intel Inside."

That lesson applies equally well to slower clockspeed industries such as automobiles. The role of electronics subsystems, for example, has evolved in the automotive industry from the early years through the 1960s when the electrical systems -- those controlling a vehicle's lights, radio, windshield wipers, starter motor, and so on -- were little more than an afterthought. In those years, the core subsystem of the automobile was its steel body, which not only defined the car's styling, a critical factor in its market reception (Ford's Edsel comes to mind), but also determined the vehicle's structural integrity, ride, handling, and manufacturability. In contrast, the electrical components had little impact on design, manufacture, costs, or sales.

Today, the dollar value of a car's electronics is overtaking the value of its steel body, and the electronic system rivals the steel body as one of the most-important subsystems: Car companies design their vehicles with a customer profile in mind, and virtually all the features that affect customers' perceptions of the vehicle are -- or soon will be -- mediated by electronics. Those features include acceleration, braking, steering, handling, and seating, as well as the communication, information, and entertainment systems.

Now consider the situation of Toyota, the third-largest automobile company in the world, and arguably the most formidable competitor in a no-longer-cozy oligopoly. Although the company maintains a virtually unassailable set of competitive advantages,[13] it has traditionally been far less vertically integrated in electronics than some of its competitors, including Ford and General Motors. In fact, Toyota has become dependent on one company -- Denso (formerly Nippondenso) -- for many of its electronic components and systems. The question arises whether Toyota will stay the course, risking the fate of IBM relative to Intel, or adjust its supply chain strategy and assert greater internal control over electronics.

The relatively slow clockspeed of the auto industry gives Toyota some time for deliberation and choice, but there may come a day when customers choose automobiles based on whether they say "Denso Inside" or "Bosch Inside" rather than by the name of the company that stamped and welded the sheet metal. As might be expected of the world's most benchmarked company, Toyota is not

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[13] Jim Womack, Daniel Jones, and Daniel Roos, *The Machine That Changed the World* (New York: Rawson Associates, 1990).

waiting around. It understands the dynamics of the fruit flies and has already begun increasing its investment in its own electronics capability.[14]

Boeing and Its Suppliers

To emphasize the contrast between fast- and slow-clockspeed industries, consider the Boeing Corporation's commercial aircraft business, which in recent decades has focused on the remarkable series of jets denoted the 747, 757, 767, and 777. Although Boeing has designed and built each one, suppliers from all over the world have made their contributions. By the late 1990s, outsourcing accounted for close to 50 percent of an airplane's total value. In fact, four Japanese aircraft manufacturers -- Mitsubishi Heavy Industries, Kawasaki Heavy Industries, Ishikawajima-Harima Heavy Industries, and Fuji Heavy Industries -- contribute approximately 40 percent of the value in airframes of wide-body models, applying specialized skills and tooling that in many cases are unique in the world.

To understand the relationship between Boeing and these Japanese suppliers, you have to go back several decades to a time when the company made its first efforts to sell aircraft in Japan. In order to win sales to Japanese airlines, Boeing needed to give Japanese companies some of the manufacturing work involved. Boeing's managers accepted those terms, setting into motion a dynamic process that has led to an important interdependency.

Both sides of the partnership have been big winners. The Japanese bought scores of aircraft, helping Boeing to become the dominant commercial aircraft company in the world. At the same time, the Boeing relationship has enabled the Japanese manufacturers to improve their technological capabilities, thereby increasing their appeal to Boeing and other manufacturers worldwide.[15] Although Boeing depends greatly on its suppliers, the company's management believes that its systems-design and integration skills will prevent any supplier or set of suppliers from wresting away industry control.

In this turtle of an industry, upheavals and reversals of fortune do not take place overnight. Yet, the examples of fruit fly industries in this book should raise a warning flag to Boeing that "Mitsubishi Inside" represents a clear if not present danger. Because of the slow clockspeeds typical of the aircraft industry, it is especially difficult to get executives in such industries to focus on the potential penalties for outsourcing key competencies -- the results typically would not come to roost during the tenure of any currently active manager. This condition suggests that companies in slow-clockspeed industries should set clear guidelines as to who

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[14] This information is based on interviews with Toyota executives conducted by Daniel Whitney, Nitin Joglekar, and Sharon Novak of the Massachusetts Institute of Technology, Cambridge, Mass., June, 1994. See also Andrew Pollack, "Move by Toyota Reported into Japanese Chip Market," *New York Times*, August 8, 1996, p. D8.

[15] See Chapter 7 in Richard J. Samuels, *Rich Nation, Strong Army: National Security and the Technological Transformation of Japan*, Ithaca: Cornell University Press, 1994.

in the organization takes responsibility for monitoring those relationships, lest time lulls the firms into a false sense of security.

4.3 Patterns in Supply Chain Evolution: The Double Helix

By examining the evolution of supply chains in fruit fly companies and industries, we can understand better the evolution of supply chains in all industries. Such an analysis has yielded a concept that we call the double helix -- a model based on an infinite double loop that cycles between vertically integrated industries inhabited by corporate behemoths and horizontally disintegrated industries populated by myriad innovators, each seeking a niche in the wide open space left by the earlier demise of the giants.

The double helix illuminates how these vertical and horizontal epochs determine the fate of companies, industries, and sometimes the economic fortunes of nations. Internal and external forces -- niche competitors, the strain of maintaining technological parity across many products, and the organizational arteriosclerosis that so often afflicts market leaders -- drive vertically integrated companies toward disintegration and a horizontal industry structure. On the other hand, when an industry has a horizontal structure, the forces exerted by powerful component suppliers and by individual firms' incentives to promote their own proprietary technologies create strong pressures toward reintegration.[16]

To observe these dynamics in vivid motion, let us turn, once again, back to the fruit flies, and to the remarkable history of the computer industry.

In the 1970s and the early 1980s the computer industry's structure was decidedly vertical (see fig. 4.1). The three largest companies, IBM, Digital Equipment Corporation (DEC), and Hewlett-Packard, were highly integrated, as were the second tier of computer makers, including Burroughs, Univac, NCR, Control Data, and Honeywell, commonly referred to as "the BUNCH." Companies tended to provide most of the key elements of their own computer systems, from the operating system and applications software to the peripherals and electronic

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[16] The double helix model portrayed here is adapted from Charles Fine and Daniel Whitney, "Is the Make/Buy Decision Process a Core Competence?" working paper, Massachusetts Institute of Technology. The model arose from our discussions over a seminar on "Technology Supply Chains" in the Fall of 1995 at the MIT Sloan School. Other observers have noted some of the same evolutionary forces. See, for example, James Moore, *The Death of Competition* (New York: HarperCollins, 1996); Clayton Christiansen, "The Drivers of Vertical Disintegration," Harvard Business School working paper, October 8, 1994, which was followed by *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Boston: Harvard Business School Press, 1997); Richard Langlois and Paul Robertson, *Firms, Markets, and Economic Change: A Dynamic Theory of Business Institutions* (New York: Routledge, 1995); and Joseph Farrell, Hunter Monroe, and Garth Saloner, "The Vertical Organization of Industry: Systems Competition vs. Component Competition," *Journal of Economics and Management Strategy*, Vol. 7, No. 2, pp. 143-182., 1998. See also the evolutionary model in Chapter 11 of Carliss Baldwin and Kim Clark, *Design Rules: The Power of Modularity* (Cambridge: MIT Press, 1999).

hardware, rather than sourcing bundles of subsystem modules acquired from third parties.

In this era, products and systems exhibited *integral architectures*. That is, there was little or no interchangeability across different companies' systems. DEC peripherals and software, for example, did not work in IBM machines, and vice versa -- so each company maintained technological competencies across many elements in the chain.

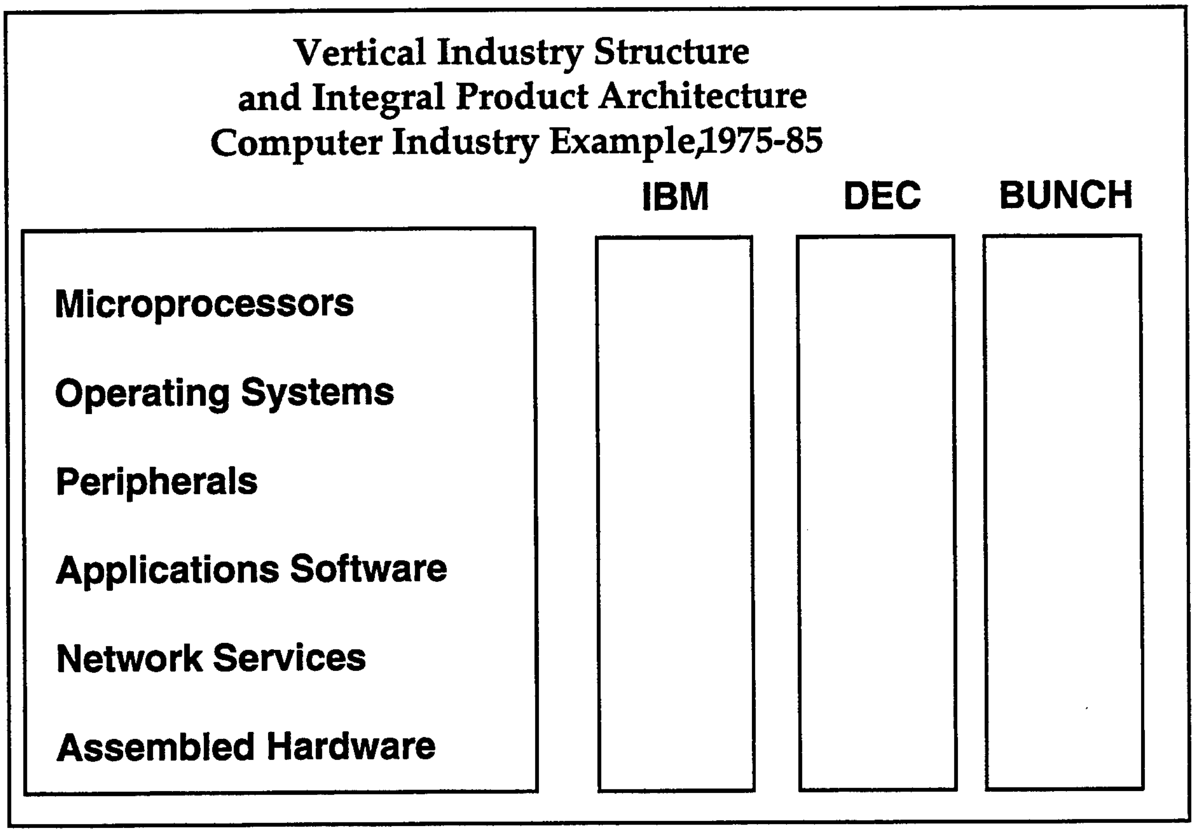

Fig. 4.1. Vertical Industry Structure and Integral Product Architecture in the Computer Industry, 1975-1985[17]

IBM had significant market power during that time and was very profitable. By holding to its closed, integral product architecture, the company kept existing customers hostage -- any competing machine they bought would be incompatible

[17] This figure is adapted from Andrew S. Grove, *Only the Paranoid Survive* (New York: Currency Doubleday, 1996), p. 40.

with their IBMs.[18] At the same time, Big Blue emphasized the value of its overall systems-and-service package, determined to stave off competitors who might offer better performance on one or another piece of the package. But storm clouds were gathering. The task of maintaining its competencies over such a broad array of technologies and capabilities was daunting, and, the pace of innovation in the industry was accelerating.

In the late 1970s, IBM faced a challenge from a new quarter. Upstart Apple Computer had cobbled together a so-called personal computer, tiny by IBM's standards, which had captured the imaginations of growing numbers of sophisticated buyers in the electronics and computer markets. In response, IBM chose to launch a new business division and a new personal computer of its own.

For the new PC, IBM's newly-created PC division turned its back on vertical integration and integral product architectures. Instead, it opted for a modular product architecture, outsourcing the microprocessor to Intel and the operating system to Microsoft. IBM's mutation catalyzed a dramatic change throughout the industry, which quickly moved from a vertical to a horizontal structure. The dominant product was no longer the IBM computer, but the IBM-*compatible* computer. The modular architecture encouraged companies large and small to enter the fray and supply subsystems for the industry: semiconductors, circuit boards, applications software, peripherals, network services, and PC design and assembly.

A single product/supply chain decision (by a dominant producer) set the stage for a momentous structural shift -- one that provides instruction for many other industrial species -- from a vertical/integral industry structure (fig. 4.1) to a horizontal/modular one (fig. 4.2). The universal availability of the Intel and Microsoft subsystems led dozens of entrepreneurs to enter the personal computer business with IBM-compatibles. The modular (mix-and-match) architecture created significant competition within each "row" of the horizontally structured industry depicted in fig. 4.2, rather than across the vertically integrated "columns" of the structure shown in fig. 4.1.

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[18] For a thoughtful treatment of modularity, see Carliss Baldwin and Kim Clark, *Design Rules: The Power of Modularity* (Cambridge: MIT Press, 1999). Baldwin and Clark argue convincingly that the IBM 360 mainframe and its followers had highly modular architectures relative to their predecessors. However, since (as Baldwin and Clark discuss) IBM chose to control all of the subsystem technologies internal to the firm, the effect was to improve the efficiency with which IBM could upgrade its products, but not to open up the architecture to competing suppliers in any real sense. My use of the term "modular" is therefore consistent with what Baldwin and Clark might call "modular and open."

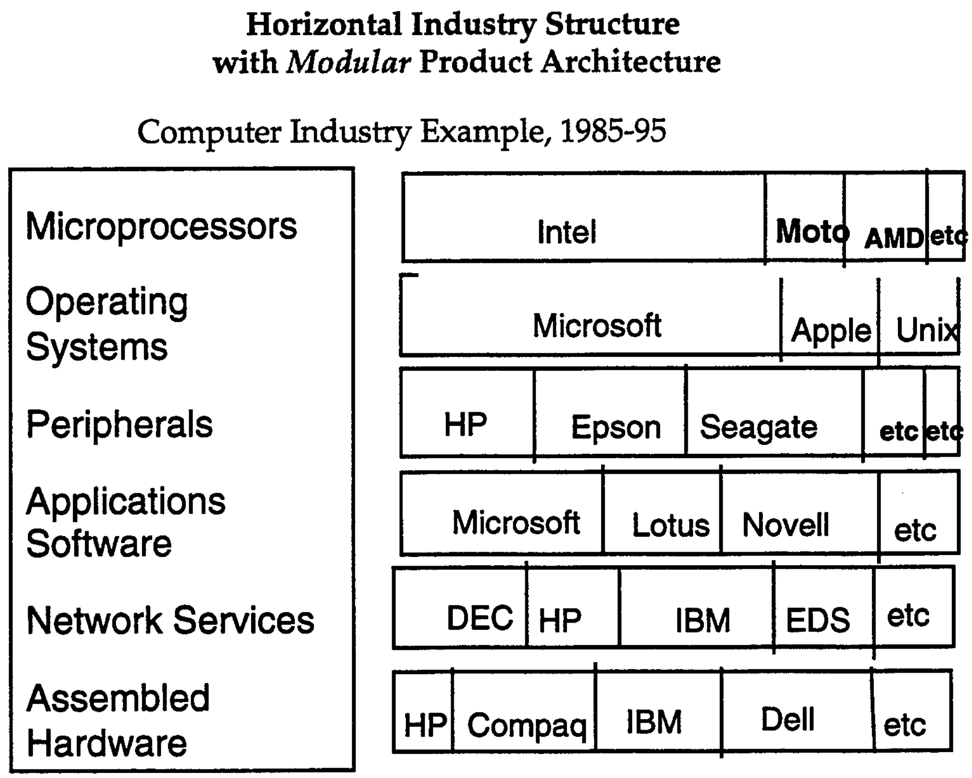

Fig. 4.2. Horizontal Industry Structure and Modular Product Architecture in the Computer Industry, 1985-1995[19]

One leader of the new era was Compaq, the first of many producers of PC "clone makers" who led the way in modularizing the industry in the image of the product's modular architecture. Compaq was nimbler and more focused than IBM. Its managers sensed what was required to go head-to-head with one of the world's most admired and feared competitors. By working closely with IBM's suppliers, Compaq beat IBM to the market in 1985 with Intel's new 80386 chip and then again with the first version of Microsoft's *Windows*. By focusing its energies and resources on product development -- and leaving technology development in the hands of its suppliers -- Compaq was running rings around Big Blue.

In this industry, so recently organized along monolithic, vertical lines, there now appeared a spate of separate sub-industries -- not only for microprocessors and operating systems, but for peripherals, software, network services, and so on. Within each of the categories, new businesses emerged, making it easier and easier for a computer maker to shop around for just the right combination of subsystems.

On balance, this spread of competition has been a healthy development for the industry and for computer buyers, but certainly not for IBM shareholders, who saw their company lose about $100 billion in market value between 1986 and 1992.[20]

[19] This figure is adapted from Grove, p. 42.

[20] Baldwin and Clark, chapter 1.

Some observers have speculated that this model of horizontal competition, which also evolved in telecommunications in the 1990s, might be the new industrial model for many industries.[21] However, further examination suggests that the horizontal/modular structure may also prove to be quite unstable -- as unstable as the vertical/integral structures that give birth to them.

Why might the horizontal/modular structure be short-lived? Let's look again at the fruit flies in the PC industry.

Horizontal structures tend to create fierce, commodity-like competition within individual niches. Such competition keeps the players highly focused on their survival. However, over time, a shakeout typically occurs, and stronger players -- those that manage to develop an edge in costs, quality, technology, or service, for example -- drive out weaker ones. Once a firm is large enough to exert some market power in its row, it sees the opportunity to expand vertically as well. Microsoft and Intel, both of which came to dominate their respective rows, have exhibited this behavior. Intel expanded from microprocessors to design and assembly of motherboard modules, making significant inroads into an arena typically controlled by the systems assemblers such as Compaq, Dell, and IBM. In addition, with each new microprocessor generation, Intel added more functions on the chip (functions that applications software suppliers traditionally offered), thereby making incursions into that row as well.[22]

In the case of Microsoft, dominance in PC operating systems has led to the company's entry into applications software, network services, Web browsers, server operating systems, and multimedia content development and delivery. In short, Microsoft looks a little bit more each day like the old IBM -- attempting to dominate increasingly large slices of the overall industry and earning monopoly-like profits in the process. Exploiting market power in this way is as old as shipbuilding – when the nations that built the best ships often controlled the most lucrative trading routes. Microsoft's ability to integrate across the rows is particularly vivid (to both competitors and regulators) because its market share is so large and information technology is so flexible.

The Forces behind the Double Helix

Fig. 4.3 illustrates the entire dynamic cycle with the double helix. When the industry structure is vertical and the product architecture is integral, the forces of disintegration push toward a horizontal and modular configuration. These forces include:

1. The relentless entry of niche competitors hoping to pick off discrete industry segments.

[21] Grove, p. 52.

[22] See Nitindra Joglekar, " The Technology Treadmill: Managing Product Performance and Production Ramp-Up In Fast-Paced Industries," PhD Dissertation, Sloan School of Management, Massachusetts Institute of Technology, 1996.

2. The challenge of keeping ahead of the competition across the many dimensions of technology and markets required by an integral system.
3. The bureaucratic and organizational rigidities that often settle upon large, established companies.[23]

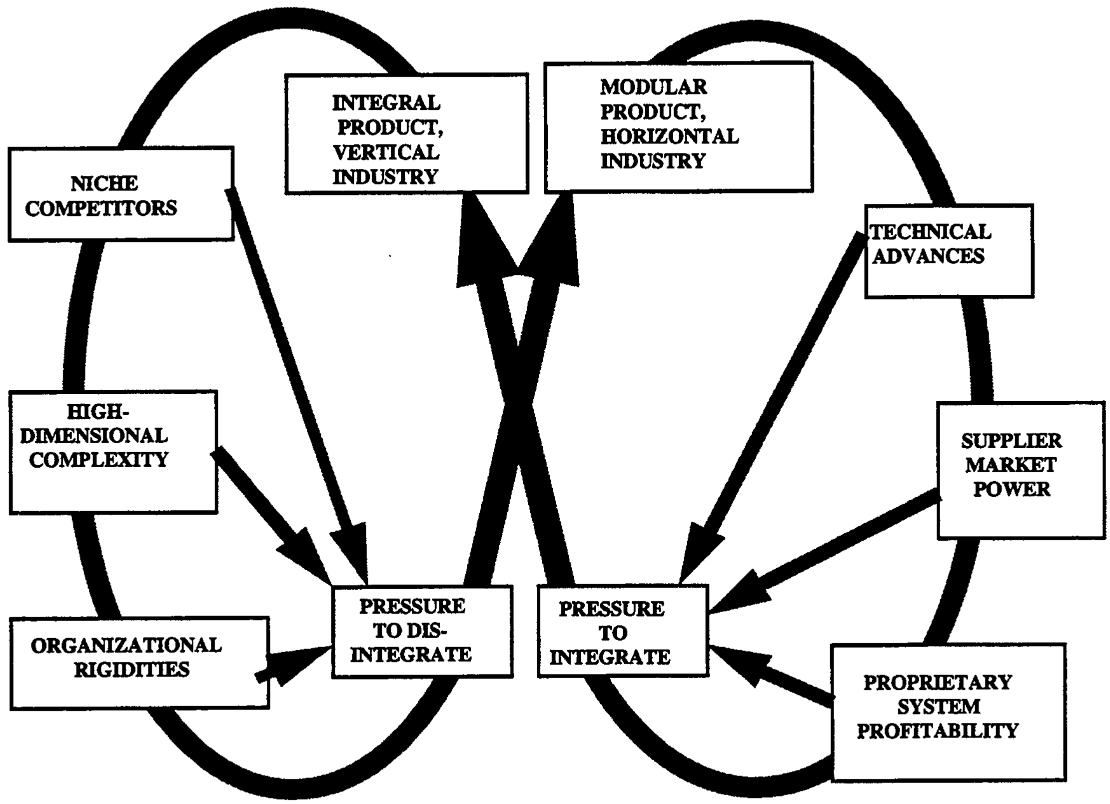

Fig. 4.3. The Double Helix, illustrating how industry/product structure evolve from vertical/integral to horizontal/modular, and back.[24]

These forces typically weaken the vertical giant and create pressure toward disintegration to a more horizontal, modular structure. IBM, it might be argued, had all these forces lined up against it: Constant pressure from niche entrants, particularly in software and peripherals; competitors who took the lead in some technological segments (Intel's invention of the microprocessor, for example); and

[23] The dynamic forces of the double helix are described more rigorously in a modeling framework in Charles Fine, Mila Getmansky, Paulo Goncalves, and Nelson Repenning, "Industry and Product Structure Dynamics: From Integration to Disintegration and Back," working paper, Massachusetts Institute of Technology, Sloan School, 1998.

[24] The double helix diagram is adapted from Charles Fine and Daniel Whitney, "Is the Make/Buy Decision Process a Core Competency?" MIT working paper, 1996. This paper can be downloaded from http://www.clockspeed.com.

the many layers of bureaucracy that grew up as IBM expanded its headcount to almost a half million employees at its peak in the 1980s.

On the other hand, when an industry has a horizontal structure, another set of forces push toward more vertical integration and integral product architectures. These forces include:

1. Technical advances in one subsystem can make that the scarce commodity in the chain, giving market power to its owner.
2. Market power in one subsystem encourages bundling with other subsystems to increase control and add more value.
3. Market power in one subsystem encourages engineering integration with other subsystems to develop proprietary integral solutions.

To apply the power of the double helix, consider the plight of Apple Computer in light of the history of the personal computer described so far. In the mid- to late 1980s, Apple's Macintosh computer was clearly the technically superior product in the PC industry. However, Apple failed to realize that the principal advantage of its computer was in its operating system, not the integral package of hardware and software it was offering. As a result, Apple tied its superior operating system in a vertical bundle to inferior hardware, whereas the IBM-compatible PC industry raced ahead, subsystem by subsystem, propelled by intense competition in each subsystem segment. In the end, the Macintosh operating system, shackled to a hardware anchor, could not match the overall rate of improvement in the modular and highly competitive PC market. Had Apple understood the dynamics of product architecture and industry structure described above, it might have uncoupled its product and controlled the catbird seat now held by Microsoft.

4.4 The Double Helix in the Auto Industry

In the United States at the turn of the century, approximately 100 "coach makers" grew up in the Detroit area, each involved in some aspect of offerings by the "horseless vehicles" industry. By mid-century, from that beginning as a horizontal, fractured industry, Henry Ford and Alfred Sloan had overseen the consolidation of the industry around a few massive, vertically integrated corporations such as Ford and General Motors. Recently, the industry has started to move back around the double helix and take on a much more distinctly horizontal/modular structure -- similar to the one we saw in the PC industry, albeit with a much slower clockspeed. In the computer industry, Compaq was the first assembler to drive the shift around the double helix. In the automobile industry, that distinction goes to Chrysler.

Compaq bought components from IBM's suppliers, bundled them into an IBM-compatible personal computer, and dramatically undercut and outmaneuvered

IBM. Chrysler began doing much the same to Ford and General Motors in the early 1990s.

Chrysler's strategists launched one of the most dramatic back-from-the-brink stories in business. In the 1980s, Chrysler was so cash-poor that to generate operating capital for survival, it had to sell its new, billion-dollar engineering center to a finance company and then lease it back. At that time, Chrysler was also in a difficult spot with its suppliers. As the smallest of the Big Three auto makers, Chrysler typically stood third in line with suppliers, who were continuously at the beck and call of the much stronger and larger Ford and General Motors. In that vertically structured era, U.S. car manufacturers tended to keep in-house the intellectual and product-development work for components and subsystems, typically outsourcing only the low-level production of individual parts according to detailed specifications. The auto makers also worked to keep component prices down by demanding bidding competitions for each job.

At one of its darkest hours, Chrysler met with suppliers and, partly out of desperation, proposed a radical change in the way the company would do business. Instead of dictating to suppliers and trying to pit them against each other, Chrysler promised to commit to long-term relationships for developing entire subsystems and to share the benefits of any cost-saving ideas with suppliers. Long the norm in many Japanese companies, this mode of operation represented for Detroit a major departure from business as usual.

At the same time, Chrysler dramatically reduced its components-development and technology-development activities and, as a result, the corporate overhead associated with them. It designs, assembles, and markets vehicles to which it contributes little of its own innovative component technology. Instead, the company relies on mutually beneficial partnerships in which suppliers grace Chrysler's autos with the latest advances.

Chrysler's strategic shift must be judged an outstanding success. From near bankruptcy, the company achieved the lowest cost structure of the Big Three and the highest average profit per vehicle. Corporate sales and profits skyrocketed. Furthermore, from having a stock price well down in the single digits, Chrysler was judged to be worth over $60 per share by Daimler-Benz when it made its historic takeover offer in 1998.

In an effort to compete with the new Chrysler, Ford and GM have also scrambled to separate their components operations from their automotive operations. Rumors that Ford or GM will sell its component operations continually resurface, a sure indicator that Chrysler has played the role of the Compaq of the auto industry. Just as Compaq helped to drive the entire computer industry to a horizontal/modular structure, Chrysler's strategy allows suppliers -- even Ford's and GM's internal suppliers -- to strengthen their capability to develop whole automotive subsystems, thereby pushing the entire structure of the industry from vertical toward horizontal.

The double helix helps us observe two phenomena: First, the assembler portion of the industry is moving from a vertical structure to a state where it is facing significant pressure to disintegrate. Second, the supplier sector is moving from a horizontal structure to a state in which there are significant incentives to integrate. Let us look at these dynamics from the perspective of each position in the chain.

Helix Strategies for Auto Makers

So what do you do if you are a player in the automotive industry? If you are an auto maker, the risks are clear: To remain vertically integrated in the face of industry disintegration is to risk the fate of IBM in the 1980s -- a slow behemoth beset by agile niche competitors. Interestingly, General Motors, the auto industry heavyweight that has lost billions of dollars and millions of car sales worth of market share in the 1980s and 1990s, has an asset it might be able to exploit: Delphi Automotive, GM's $32-billion-a-year auto parts powerhouse. If, as the fruit flies have taught us, the automotive industry is headed for an era where suppliers may take control, it is certainly vital to note that by far the biggest and strongest automotive supplier on the planet is wholly owned by General Motors. The trick for GM will be balancing the health of the child with that of the parent. IBM lost control of its industry partly because the entrenched mainframe division could not stand the thought of subjugating itself to the upstart PC division. Will GM's car folks stand in the way of Delphi's rise to power? Managing that balancing act will be key to GM's future.

In the case of Toyota, there is no asset such as Delphi to help hedge against the danger of "Denso Inside" overtaking what we might call "Toyota Outside." What Toyota has, however, is the world's premier lean machine of the automotive world. The company has a tremendous lead in the combination of cost, quality, and development speed. Its knowledge base of automotive development and technologies is very deep. And, its ability -- and willingness -- to explore new technological frontiers (such as hybrid gasoline-electric engines) is impressive. These assets probably assure Toyota safe passage unless an extremely powerful player in components or retailing emerges.

A recent *New York Times* article reported on a joint venture between a Toyota subsidiary and Texas Instruments to build a $1.5 billion semiconductor factory that would make memory chips and automotive electronic components. The article also noted Toyota's earlier moves into telecommunications and software, and it twice used the word "puzzling" in reference to Toyota's strategy behind this venture.[25]

To a student of business genetics, however, these moves are anything but puzzling. They indicate clearly that Toyota managers have intuited the lessons of the double helix, concluded that auto industry clockspeed will approach that of the electronics industry, and that some car companies may fall victim to the automotive

[25] Andrew Pollack, "Move by Toyota Reported Into Japanese Chip Market," *The New York Times*, August 8, 1996, p. C8.

equivalent of "Intel Inside" computers. Thus, they are continually adjusting their supply chain design to position themselves for the coming changes.

If you are Chrysler, you play the Compaq/Dell strategy to the hilt. Chrysler leads in that strategy by a large margin. If you are Daimler-Benz, you either follow the Macintosh strategy -- higher quality to a small, discerning niche -- or you buy a Chrysler and try to be a premier, full-line player such as Toyota. That's a tough row to hoe, but it may be more promising than playing Apple among increasingly powerful suppliers and large, powerful rivals.

On balance, the world's major automotive manufacturers are adjusting their strategies for a tougher, faster-clockspeed world, but they are not acting as if they believe a turn in the helix is inevitable in the short term. Because the automobile as a manufactured product may never be as modular as the Windows-plus-Intel PC, this could be the best course. In the automotive supplier sector, however, the preparations for a horizontal/modular world are in full swing.

Helix Strategies for Auto Suppliers

The players that produce automobile seating systems illustrate well an aggressive stance toward the turn to horizontal/modular. For most auto makers, seats are the biggest single externally purchased item for their vehicles -- more than $1,000 per set in some cases. Through the 1980s, most Big Three car makers, consistent with the vertical structure of the industry, designed and assembled seating systems, but purchased the seat parts -- the metal frames, fabric, and electronic controls. By the mid-1990s, however, the seat industry was dominated by giants such as Lear and Johnson Controls, each of which saw its annual sales skyrocketing from under $1 billion to more than $7 billion. In this new environment, when an auto maker begins to plan the seats for a new vehicle, there is a limited set of possible suppliers, each of which has significant clout in the industry.

Furthermore, these seat companies have begun to acquire related businesses -- suppliers of interior panels and carpets, for example. Thus, if Ford, for example, wants to specify Lear seats for a new car, it may be told, in effect, "We're not a seat company anymore. We are now an interiors company. If you want our seats, you have to buy the whole integral automobile interior: our carpets, our headliners, and our dashboards as well." Because Ford has a limited choice of seat suppliers and because each seat supplier seems to be pursuing a similar vertical integration strategy, a pattern begins to emerge: Once niche players have built significant market power in the now horizontally structured industry, they often move vertically to exploit their newfound market power. This activity is little different from Intel's bundling of graphics chips with its microprocessors or Microsoft's bundling of its web browser with Windows.

Despite the depth and market power of suppliers such as Delphi, Bosch, Denso, Johnson Controls, Lear, and others, no one in the auto industry has a monopoly grip that even approaches that of Intel or Microsoft in the computer industry. And, although suppliers are consolidating across subsystems -- a sort of hedging strategy like the one we saw in the MICE industry in chapter 2 -- auto makers can still play suppliers against each other. That game, however, is much trickier than it once was because of the dramatic increase in industry concentration in many segments. A supplier that becomes too ambitious too fast can find itself shut out of many car programs. Yet, a supplier that is too timid can find that its competitors are winning contracts by flexing their muscles in exactly the way that Intel did when it launched its "Intel Inside" campaign -- by going directly to the final consumer.[26] In the computer industry case, a typical consumer in effect tells the sales channel: "I don't care who made the box, just give me 'Intel Inside.'"

If this type of campaign can work with a computer chip, which customers can neither see nor touch, then surely it has a chance to work in the automotive industry, where visual and tactile appeal count a great deal in a customer's evaluation of the vehicle. Certainly, customers can be made much more aware of the value they place in the seats or electronic controls in a car. However, even for lesser systems, direct advertisement to the customer might prove fruitful. Consider the following example: In 1996, UT-Automotive, a broad-based supplier of components and subsystems to the automotive industry, ran an advertisement in a number of business magazines touting its electronic security systems. The print ad featured a photo of a high-tech car thief, who used a device to capture electronically the code to a car's security system as the owner "beeped" it into the alarm mode with a remote key-chain device. UT-Automotive's ad boasted a security system feature that could scramble the code and reset it with each use, so that the code picked up by the thief would not be the right code for the next deactivation of the alarm. The ad noted that the system was available on some GM, Honda, and Nissan vehicles, in effect saying: "You shouldn't focus on who made the box; just ask for 'UT-Automotive Inside.'"

The suppliers in the automotive world have far more to gain from a shift to horizontal/modular than do the assemblers, except perhaps for Chrysler since it has already aligned itself with such a model. The suppliers, in addition, have girded themselves for war should one arise. I believe the auto makers should be wary. The PC industry teaches us that once the horizontal/modular trigger has been tripped, neither market share nor technological depth, neither financial strength (in the case of IBM) nor superior product technology (in the case of the Apple Macintosh) can withstand a tidal wave of exuberant entrants into the breach.

Because even a Toyota could probably not retain its standing if all other firms evolved into horizontal/modular structures, the critical concern of auto makers is how to prepare for and hedge against a major industrial shift. Individual capabilities that are critical in one era may become commodities in the next. As a result, more important than any individual capability -- in technology or

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[26] Interestingly, the success of the "Intel Inside" campaign rested far more on marketing than on technology. Through advertising, Intel was able to convince millions of computer buyers that when they go to a computer store, the key feature to seek out is that "Intel Inside" logo. Yet, the microprocessor of a computer is not, in any way, an experiential good: Customers can neither see nor touch that computer chip. Most users could not tell whether an Intel chip was inside the box they purchased if it were not for the logo on the outside.

manufacturing, for example – is the ability to foresee the coming changes and choose which capabilities will be of greatest value.

5. Strategic Supply Chain Design

5.1 Dell Computer's Superior Supply Chain Design

To begin, let's look at the role of chain design through the handiwork of one of the most inspired supply chain designers on the planet: Michael Dell. As of May, 1998, the stock price of Dell Computer had increased 26,900 percent in the decade of the 1990s – higher than that for Intel, Microsoft, Coca-Cola, Disney, or Cisco Systems.[27] Dell Computer has no proprietary technology propelling it to such stratospheric growth and profitability. In fact, the company's position in the supply chain has it squeezed between Intel and Microsoft upstream, two of the computer industry's most powerful players, and a downstream market populated by millions of well-informed consumers who can choose from dozens of computer companies that assemble almost indistinguishable personal computers. In terms of direct rivals, Dell must contend with powerhouses IBM, Hewlett-Packard, Compaq, plus myriad low-cost Asian and American players who have taken advantage of the low costs of entry into the PC industry. By any Porter-style analysis,[28] Dell's industry position looks anything but attractive.

Yet Dell not only thrives, its sales and profit growth can take your breath away. The company's primary advantage is its preeminent supply chain design, augmented with precise supply chain management. Although difficult to believe, throughout the 1990s Dell's supply chain *management* has been driven by "vintage software" for materials requirements planning (MRP).[29] The story of Dell's success is fascinating and important, in part because it illustrates a brilliant supply chain design in a fast-clockspeed industry.

Using parts ordered from catalogs, Michael Dell began assembling and selling computers from his dormitory room at the University of Texas. When his roommate kicked him out because of the electronic clutter, Dell just moved to bigger quarters and has continued to expand ever since. Fortunately, Texas is a big state and has afforded him plenty of space to grow.

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[27] "Michael Dell Rocks," *Fortune*, May 11, 1998, pp. 59-70.

[28] Michael E. Porter, *Competitive Strategy* (New York: Free Press, 1980). Porter's "five forces" model suggests assessment of one's competitive position by examining the power of buyers and suppliers as well as the rivalry among competitors, opportunities for new entrants, and availability of substitute products (p. 4).

[29] Stuart Smith, "Capitalizing on Clockspeed in the Direct Business Model," paper presented at "Creating and Managing Corporate Technology Supply Chains: Value Chain Design in the Age of Temporary Advantage," symposium at the Massachusetts Institute of Technology, Cambridge, Mass., May 12-13, 1998.

Dell Computer takes orders for customized PCs and workstations over the telephone and on its Internet site, begins building the machines almost immediately after the orders are complete, and ships the completed products as soon as they are built, often within 24 hours. The company carries no finished goods inventories, nor does it employ any distributors or retailers who carry inventory. It ships all products directly from its factory to the final customer. Furthermore, Dell carries almost no materials inventories: Every part the company buys goes immediately into a machine that is then built and sold.

How does Dell know what it will sell? To understand the answer, it helps to frame the question the other way around: Dell sells whatever it has purchased. The only variable is price.[30]

Dell's sales organization is responsible for forecasts and decisions on what components to purchase. Because commissions are based on Dell's profit margins, salespeople must sell whatever they order, including components for which buyers misjudged customer demand. If demand falls or customers no longer want a component, the sales organization must lower the price so that the product sells no matter what.

How does the company avoid getting burned? First, it gets good prices from suppliers because it buys in volume. Second -- and this is the real key -- if in doubt about likely customer preferences, buyers always opt for ordering components of latest technology because those have the longest shelf life. Because the company carries no inventories and has no resellers, it can be the lowest-cost producer. In addition, because high-end users usually purchase the latest components, Dell services this select group and keeps its profit margins healthy (see fig. 5.1).

And here's the real kicker: The faster the clockspeed of the computer industry, the greater the advantage Dell wields over its competitors. How does this work? Every other major PC maker builds to stock and sells through resellers who carry inventory. In this industry, inventory does not age gracefully.[31] In fact, aged inventory in the computer market is downright ugly. What could be worse than holding a large inventory of PCs with built-in 28K modems when the new 56K modems hit the market? Who would have wanted to have on hand several thousand Pentium processors when Intel introduced the Pentium II and prices of the old Pentiums dropped through the floor?

In the lightning-speed PC industry, such obsolescence is practically an everyday occurrence. The more inventory in the chain, the higher the obsolescence costs. And the faster the clockspeed, the higher the obsolescence costs. So, whoever has the leanest chain wins -- and the faster the clockspeed, the larger the margin of victory. No wonder Michael Dell is printing money.

[30] Ibid.

[31] Ibid.

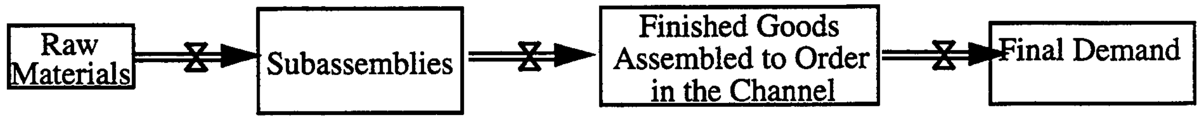

Fig. 5.1. Dell's Supply Chain

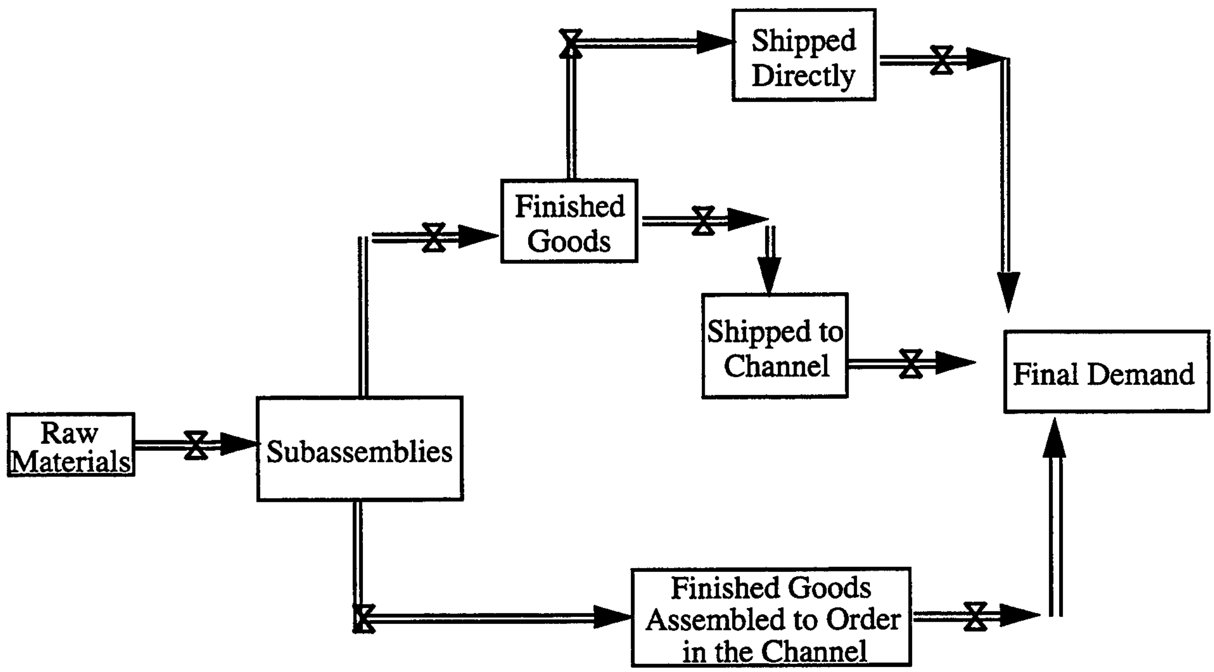

Fig. 5.2. Standard PC-industry Supply Chain[32]

Why can't Compaq, IBM, HP, and the others just copy Dell's model, given that there are no secrets or proprietary patents? Actually, those companies are trying to do exactly that, as fast as they can. The problem is that they are all dependent on their current channel resellers for sales (see fig. 5.2). Any attempt to eliminate those resellers is likely to cause sales to plummet until the new model is fully worked out. Meanwhile those lost sales will go to Dell Computer Corporation or another competitor and may not come back. Thus, the resellers/channel-

[32] This diagram was developed by Nitin Joglekar, "A System Dynamics Model for Benchmarking the Effectiveness of 'Made-to-Order' Decisions against 'Made-to-Stock' Alternatives," unpublished paper, May, 1998.

dependent producers are forced to adopt a gradual conversion rather than go cold turkey, so to speak. But a gradual conversion in a fast-clockspeed industry can seem like a lifetime. As a result, Dell Computer remains in the driver's seat -- for now.

Dell Computer Corporation illustrates a richer way of thinking about supply chain design -- not as a static collection of contractors, but as a company's most important competency. Most of the literature on business strategy has focused on the individual corporation as the appropriate unit of analysis. In this line of thinking, the supply chain is taken as given, and the challenge is characterized primarily as managing the chain: stewardship of the relevant network of organizations and assets to provide value to final customers.

This static, passive view of supply chain design, however, is inadequate to describe what is actually happening in the personal computer industry, where companies are continually reassessing their supply chain designs in search of temporary advantage. Considering the industry's fast clockspeed, firms must pay attention to designing the *extended* organization, defined here as the corporation per se as well as its supply network, its distribution network, and its alliance network.

Just as the manufacturing management community discovered in the 1980s the enormous power of the product *design* activity for leveraging improvements in product *manufacturing* performance, a well-designed supply chain offers enormous payoffs in managing the activities of the extended company. Supply chain design ought to be thought of as assembling chains of *capabilities*, not just *collaborating organizations*, in the quest for a series of temporary advantages. Since no advantage lasts forever, these design activities must be ongoing, and therefore constitute the "core" capability of a firm in a dynamic economy. Top-performing companies distinguish themselves from the ordinary by their ability to anticipate better where in the chain lucrative opportunities are likely to arise and to invest in the capabilities and relationships to exploit them. Especially in the long run, fortune favors the prepared firm. Therefore, superior market and technological forecasting ability and superior competency portfolio management (that is, supply chain design) are critical organization functions.

Jazz musicians who jam in the same place day after day learn to create great art by inviting other musicians to join them, people who might be passing by and interested in a short gig. There's a core of players, but the real creation is not theirs alone. That opportunity arises when outsiders, some of whom may be very talented musicians, join the creative process. Once everyone feels the rhythm and intuits the direction of the musical line, the creation is spontaneous but not entirely subject to accident or fortune. A lead musician still directs the burst of inspiration and innovation.

Similarly, a company's *real* core capability -- the inner core, if you will -- lies in the ability to design and manage the supply chain in order to gain maximum advantage, albeit temporary, in a market where competitive forces may change at lightning speed. To see a corporation piecemeal, element by element, affords but a limited and usually distorted sense of the entire enterprise. One might just as well study a heart or a liver in hopes of determining what sort of person the owner is.

Looking at a company in the context of its supply chain and stakeholders renders a much fuller view, a holistic image of activities, a seamless chain of capabilities or know-how -- both its own and that of the organizations with which it is allied. Like the world around them, these capabilities and the relationships among them are constantly changing and evolving. Therefore, a company must monitor and manage them all.

In a fast-clockspeed world especially, companies must focus strategic thinking on their entire value chain, not merely on individual capabilities. Individual capabilities can lose value overnight, hastened by new or rapidly evolving technologies or by the new tactics of competitors. These observations are borne out by three cases from vastly different

5.2 Supply Chain Mapping

Consider Chrysler Corporation. During the 1990s, Chrysler became a corporate pacesetter in making supply chain design a core competence of the corporation. The leader of this endeavor was Thomas Stallkamp, who designed and executed this process as executive vice president of procurement and supply. In 1997, against all traditions in the industry, Chrysler's board of directors named Stallkamp as the company's new president. Then in 1998, when Daimler-Benz launched its merger with Chrysler, the newly announced organizational structure featured two CEOs, one each from Chrysler and Daimler-Benz, but only one worldwide president: Stallkamp. As the clockspeed of the automotive industry accelerated in the 1990s, Chrysler and Stallkamp led the field in applying fast-clockspeed principles to supply chain design.

Chrysler estimates that approximately five million people and 100,000 organizations are involved in the company's Extended Enterprise™. And each person and organization in this network can affect in some way the customer's perception of quality even as she drives her new car or used truck off the dealer's lot and onto the road. Appropriately, Chrysler finds it humbling to contemplate the complexity of coordinating a massive meta-organization of this scale. Consequently, in the early 1990s, the staff of Chrysler's Procurement and Supply organization decided to begin mapping this enormous system.

The staff began with the Jeep Grand Cherokee -- one of Chrysler's most important products at the time.[33] Going one step up the chain, they examined the source of Jeep's V-8 engines -- obviously an important subsystem in the vehicle -- which are manufactured in one of Chrysler's own plants.

At the next level of the chain, the team traced the source of a roller-lifter valve -- a small, but critical, component in the engine. This component was supplied by Eaton Corporation, a large, global automotive supplier that manufactured the lifters in large quantities.

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[33] This anecdote was related by Barry Price, Chrysler's executive director of platform supply at the symposium "Creating and Managing Corporate Technology Supply Chains," Massachusetts Institute of Technology, Cambridge, Mass., May 10-11, 1995.

At the chain's next level, the team visited the source of the raw metal castings that the Eaton Corporation precision-machined for the roller-lifter valves. These castings were sourced by Eaton from a small shop near the Eaton factory. After visiting this casting shop, the Chrysler team chose to go back even further to visit the company that supplied the clay for the foundry where the castings were made.

Upon visiting the clay supplier, the team made a remarkable discovery: This supplier, which provided clay of a unique chemistry needed by the casting company, had for some time lost money in its business. Without informing any other members in the chain, the company owner had decided to get out of the unprofitable casting clay business and reorient his business to processing the same raw materials into kitty litter! Imagine how the Chrysler executives must have looked at each other in horror as they quickly realized that this strategic move into kitty litter could soon shut down manufacturing of one of the most profitable product lines in the entire Chrysler Corporation.

We found another case study, with a semiconductor company that experienced high maintenance costs on a bottleneck process for several of its capital-intensive chip plants. Upon exploring the supply chain for one of the key high-consumption spare parts required for the maintenance operation, company managers found a "gem" at a fourth-tier metal plating supplier: Employees at a key plant were dumping the highly toxic chemical plating wastes into their backyard. This was triply horrifying to the semiconductor company because of the environmental destruction, the potential liability to all members in the chain for that destruction, and the potential loss of output from shutting down the plater if a replacement could not be found quickly.

As a business manager, you can trace the production sources of every item used in creating, distributing, and marketing of your products. The power of this mapping lies in the sometimes shocking discoveries you will make, discoveries that can help you avoid potential crises down the road if you take the necessary steps now to correct the problems. But to take full advantage of this prediction of present or future stress points, you will need to master the cartographer's skills.

In a typical atlas, one map color-codes the average rainfall or temperature in all the cities of the region. Another illustrates population density or income distribution. A third shows the gradations in elevation. To begin to understand the region thoroughly, you have to examine all the maps. Similarly, to understand a capabilities chain thoroughly, you have to view it -- map it – in multiple dimensions: organizations, technology, and capabilities.

This chapter presents four cases studies to illustrate the variety and richness of the chain maps that may be plotted and the clockspeed analyses that can be extracted from them. We first continue the Chrysler case study above to show the three levels on which chains may be mapped: the organization chain, the technology supply chain, and the capability chain. Next we present a case from AlliedSignal in chemical production, which illustrates that within these chains one can observe and respond to management challenges due to acceleration in product clockspeeds, process clockspeeds, and organization clockspeeds. Finally, we present a dynamic clockspeed analysis methodology, which is then illustrated for cases in the defense aerospace and information-entertainment industries.

Three Chain Maps at Chrysler

Consider the three chain maps illustrated in figure 5.3, which elaborate upon the Chrysler story above. The diagram indicates three levels of supply chain mapping that can be used to identify various pitfalls and opportunities in the chain. The first level -- *mapping the organizational supply chain* -- is straightforward conceptually, but can be difficult logistically, because of the large number of entities in the chains of many organizations. The data required, however, for this effort will typically be maintained by the organization in its customer and supplier databases. The second and third levels -- *mapping the technology supply chain* and *the business capability chain* -- are both conceptually and logistically more challenging to develop. Most of the data required to develop them is not in any organizational database, but needs to be constructed by people intimately involved in the technological and business processes of the organization.

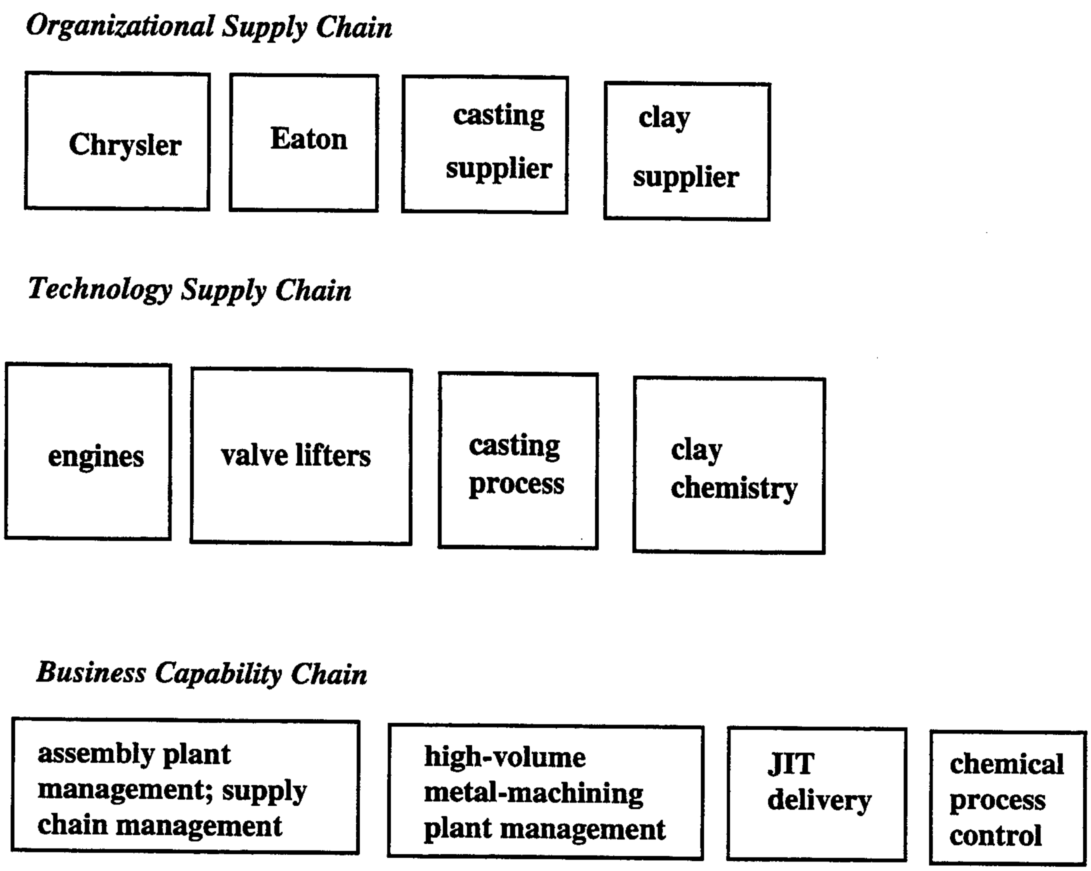

Fig. 5.3. Organizational Supply Chain, Technology Supply Chain, and Business Capability Chain

Chain mapping affords valuable tools for revealing risks and opportunities in the value chain. Managers will be most familiar with the organizational supply chain map, which arrays the entire set of organizations -- all the way from the uppermost supply tiers -- that add value in the chain to the final customer. Although easy to conceptualize in the abstract, this task can be enormously complex in actuality -- as evidenced by Chrysler's estimate of the 100,000 organizations in its extended enterprise.

Because mapping such an entity in its entirety is clearly a monumental task, you must be judicious in choosing which strands to illuminate and explore in greatest detail. The most important to explore carefully are those with clear strategic importance and those with fast clockspeeds since fast clockspeed domains are the most likely to create dramatic industrial restructurings.

Drawing such a map is not unlike creating a family tree. Taking either a product or a process view of your organization, you begin by enumerating each of your suppliers who provide raw materials or components (be sure to state what these are) that your company uses to provide its products and services. Next, trace any connections that these suppliers may have with each other (for example, is one company providing the same raw materials both to your organization and to one of your suppliers?). Such an analysis can be valuable for pinpointing possible future conflicts if suddenly the supply of that raw material is jeopardized. Next, enumerate suppliers in the next tier -- that is, those who supply the suppliers, as in the case of the clay supplier who provided a necessary product to Chrysler's casting shop. This part of the cartography can become extremely complex and intricate, and there is no limit to the number of tiers you can represent in the map. The essential value of the map lies not so much in the details of its intricate connections, but in the accuracy of the predictions it allows you to make about the future of your company or industry.

The next challenge is to attack the mapping of the technology supply chain. Even if a firm's technology is relatively simple and straightforward, as in the case of an Internet server and electronic mail, it is important to trace the lines of dependency from your organization upstream and downstream to the suppliers and customers who provide and use the technologies that lie out of your immediate sight. These dependencies can turn out to be pivotal.

Product and process engineers must sit down with procurement and supply experts to sort through the product bills of materials and the process plans for fabrication and assembly. Drawing a map of the key technologies deployed in the company's value chain helps you not only visualize the connections between the technologies and your company's capabilities, but also plan for alternatives if technologies fail or become unavailable. Like the organizational supply chain, the complete chain map typically will be vast. Therefore, much judicious thought must go into identifying the high-leverage, high-risk, high-clockspeed, and high-opportunity elements in the chain -- then mapping them into a usable tool.

The map outlined in fig. 5.3 highlights a few of the key technologies in the Chrysler chain -- engines, valve lifters, casting process, and clay chemistry. Other examples include the genomics-related technologies critical to Merck, the bicycle components purchased by Schwinn, and the photolithography technology used by Toshiba. In each case, there is not one, but an entire chain of technologies to be elucidated and examined.

Perhaps the most conceptually challenging is the business capability chain. To map it requires a team comprising experts in your organization's key business processes -- product development, research, production, purchasing, logistics, human resources, and so forth. This team should be tasked with identifying and mapping the key business process capabilities along its value chain.

Again, the map in fig. 5.3 shows several key capabilities in the Chrysler chain: assembly plant management, supply chain management, high-volume metal-machining plant management, JIT delivery, and chemical process control. Other examples include website development at amazon.com, continuous product upgrading and logistics management at Dell Computer Corporation, and management of science-based research and development at Merck.[34]

[34] For more detail, see Charles H. Fine, *Clockspeed: Winning Industry Control in the Age of Temporary Advantage,"* Perseus Books, 1998.

5.3 Bringing the Maps to Life with Clockspeed Analysis

Analyzing the static maps of the organizational supply chain, the technology supply chain, and capability chain can help you discover hitherto hidden facts about the supply chain and provide insights that can deeply affect the setting of corporate strategy. Still more valuable insights come from examining the chain maps and their constituent parts in conjunction with dynamic clockspeed analysis.

The beauty of clockspeed analysis is that it is simple, but powerful. Beginning with the three basic maps described, then, for each element of the chain, ask a series of what I call the clockspeed analysis questions:

1. What is the clockspeed of this chain element and the industry in which it is embedded?
2. What factors (for example, increased competition from new entrants, new technological innovations in the industry, new regulations, and the like) are driving the clockspeed of this element?
3. What are the prospects for a change in clockspeed in this chain element as a result of expected changes in competitive intensity or in rates of innovation?
4. Where is its industry located on the double helix? That is, is the industry primarily in a stage of horizontal structure with modular parts or primarily vertical with highly integrated parts?
5. What are the current power dynamics for this element in the chain?

The following examples illustrate how the clockspeed analysis questions can help illuminate the usefulness of the capabilities chain and assist managers in predicting future events.

Lockheed Martin Defense Aircraft Clockspeed Analysis [35]

Consider the challenges of developing a state-of-the-art jet fighter. The end of the 1990s features a contest between the two largest aerospace companies in the world, Boeing and Lockheed Martin, competing to win the prime contractor role for the "Joint Strike Fighter" (JSF) jet that is expected to provide the mainstay of U.S. airborne military capability for the first half of the twenty-first century. The total lifetime value of the contract has been estimated at over a third of a trillion dollars.[36]

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[35] This case is based on the field work of Richard Keiser while he was an M.S. student in MIT's Technology and Policy Program, and on Richard Keiser and Charles Fine, "Technology Supply Chains in the Defense Aerospace Industry: Lockheed Martin Tactical Aircraft Systems," unpublished paper, Massachusetts Institute of Technology, Cambridge, Mass., 1997.

[36] Jeff Cole, Andy Pasztor, and Thomas Ricks, "The Sky, The Limit: Do Lean Times Mean Fighting Machines Will Be Built for Less?" *Wall Street Journal,* November 18, 1996, pp. A1, A7.

The "fly-off" competition is expected to occur in the first decade of the second millennium, and volume production is expected to begin in 2008.

The development challenges for this project are staggering. Among them is the need to reconcile the high clockspeed of the electronic capabilities of military warfare with much slower clockspeed of airframe evolution and the long time scale of the project.

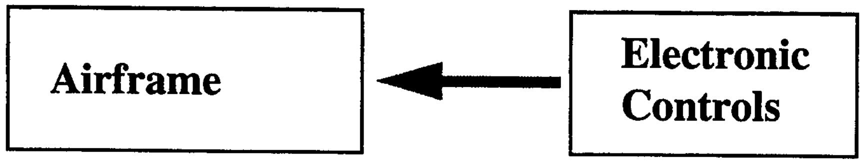

Fig. 5.4. Two components of the Joint Strike Fighter (JSF) technology supply chain.

Fig. 5.4 provides a simple diagram of two components of the technology supply chain for this project: the airframe and the electronic controls. To be concrete in illustrating the analytic approach, I will make some assumptions about the facts of the case where precise numbers are classified or not available.

The first of the clockspeed analysis questions -- namely, what is the clockspeed of this chain element and the industry in which it is embedded? -- suggests estimating clockspeeds for the products and processes involved. Let's suppose that major technological improvements are expected to occur roughly every three years in the controls domain and every ten years in the airframe domain. (Three years is far longer than the interval of consecutive Intel microprocessors, for example, but more in line with slower-evolving complex software systems, such as Microsoft's Windows.) Further, let's suppose that the processes for electronics and airframe manufacture undergo major technological improvements every five years and ten years, respectively. Given the faster clockspeeds in the electronics arena, designing the jets in order to equip them so that they have the latest electronic control systems is a major challenge and critical to the aircraft's performance. One need study military history no further back in time than the Gulf War with Iraq in the early 1990s to appreciate the value of superior electronics.

The second question of the analysis asks what factors are driving those clockspeeds. For the electronic controls, the clockspeeds are, in part, driven by hardware innovations from the electronics industry that are completely outside the control of the aircraft industry. On the other hand, software development in electronics controls to exploit the latest hardware is driven by the tradeoffs in the costs of developing and writing new software and the expected benefits. Those benefits depend on the state of the competition's capabilities and technologies, which may be influenced, say, by the state of the arms race at a given moment in history. The clockspeeds of airframe products and processes, in contrast, are much more directly influenced by investment rates within the aircraft industry itself.

The third question -- what are the prospects for a change in clockspeed in this chain element as a result of expected changes in competitive intensity or in rates of innovation? – requires some crystal-ball gazing and reliance on what technology companies say about future developments in their industry. In the electronics domain, for instance, Intel has claimed that it can keep up the pace in developing microprocessors and semiconductors well into the second decade of the twenty-first century.[37] In software development, estimates are likely to show greater variance, depending in part on the pace of software development tools. In the case of airframes, one possible factor in development might be aggressive investment in composite materials development by the automotive industry. This scenario seems unlikely since the aircraft industry has typically led the automotive industry in advanced material usage, although a new set of policies to radically reduce automotive emissions and fuel consumption is possible during the lifetime of the JSF project.

Fourth, we ask where on the double helix is the industry located. Is it primarily horizontal and modular or vertical and integral? In electronics hardware, for instance, the industry and supply chain are currently horizontal and modular, with little momentum toward a more vertical structure. In fighter jet controls software, the structure is much more vertical and integral, and there are very few players in the world who can supply the required technology and knowledge base. In airframe products and processes, the available supply chains include the major aircraft makers in the world, most of which have modularized their supply chains to some degree so that they can outsource significant amounts of component fabrication. However, given the consolidation in the U.S. aircraft industry in the 1990s, we might expect that little additional integration will occur and that any movement along the double helix is likely to be in the horizontal/modular direction, although probably at a slow pace consistent with historical clockspeeds in the industry.

With respect to dependency dynamics in the chain (the fifth clockspeed analysis question), the jet makers will likely continue in their dependence on electronics supply chains for hardware, but given the absence of high concentration in that industry, this dependency will likely pose few strategic problems. In controls software, the major firms are dependent on some suppliers for subsystem controls, but tend to keep "in house" the system's design and integration because of the direct dependency of overall system performance on this function. In the case of airframes, the jet makers tend to do the design and assembly internally, but outsource the fabrication. Depending on the part of the airframe, some of the fabrication components are sourced in markets where few suppliers could provide the capabilities.

For the sake of space and exposition, this analysis has taken a very simplified view of an enormously complex project. Nevertheless, assessing the answers to these five clockspeed analysis questions does yield useful insights. First, the rapid clockspeed of the electronics sector and the structure of the supply chain for

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[37] Randy Bollig, director of corporate capital acquisition, Intel Corporation, presentation at the Massachusetts Institute of Technology, Cambridge, Mass., January 21, 1998.

electronics suggest several policies for the jet manufacturers. For example, the aircraft product design, the controls software, and the development and manufacturing process must allow for some modularity in electronics so that new hardware developments from suppliers can be integrated into the product. Furthermore, given the confidence of firms such as Intel in its ability to continue to push hardware performance, some of those projections probably ought to be designed into the systems. Vertical integration into the hardware would be expensive and might not provide competitive hardware advances.

Second, although airframe design and assembly have traditionally been considered as absolutely core to aircraft suppliers, the relatively slow clockspeed of the technology, the availability of a number of airframe makers around the world, and the fact that any relevant innovations in airframe materials are likely to come from existing or new suppliers, all suggest that some amount of airframe outsourcing would be strategically safe. Keeping airframes solely inside might be optimal given the integrality of the airframe with other subsystems (such as weapons or cockpit), but within the example examined here, some outsourcing, given the right supplier opportunity, seems reasonable.

Of course, all these arguments apply readily to a peacetime situation, but would certainly be tested vigorously in the event of war. In that case, which is arguably the only one that really matters, assemblers presumably want on-shore supply capability. As discussed earlier, Boeing's commercial business does not have this (and may not need it). However, in defense aircraft, supplier location and nationality is surely an important consideration.[38]

Information-Entertainment Clockspeed Analysis

To show contrast with the slow-clockspeed aircraft industry, let's consider a light-speed example, this one from the entertainment production and distribution industry, where the likes of Disney, Paramount, and Universal compete at a pace that rivals the life cycle dynamics of the fruit fly. For the sake of illustration, a simplified relationship between production and distribution is presented in fig. 5.5.

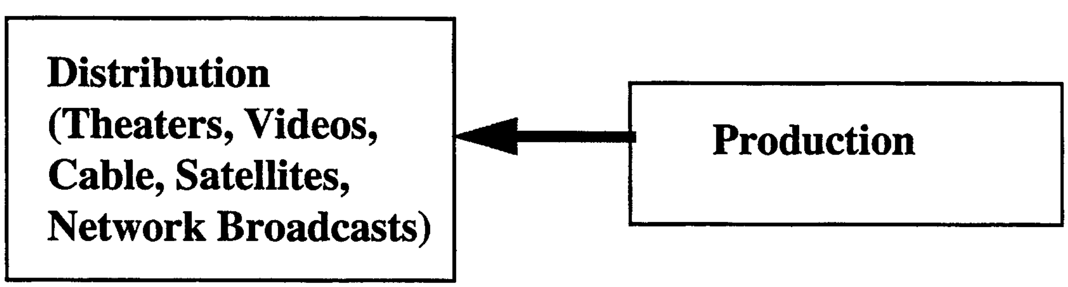

Fig. 5.5. Two Components of the Entertainment Technology Supply Chain

[38] I am grateful to Dan whitney for emphasizing this point.

For the first two clockspeed analysis questions (clockspeed measurement and drivers), the improvements in digital image manipulation that allowed creation of hits such as *Jurassic Park, Titanic,* and *Toy Story* have hastened the clockspeed of movie production technology. Although this evolution is continuous rather than discrete, we can conservatively peg the turnover rate at once every two or three years. In distribution, enhanced Internet and telecommunications technologies, as well as a proliferation of new distribution channels, suggest a rate where one might expect a new, important technology to appear almost on an annual basis, if not quicker.

In both production and distribution, the clockspeed is driven primarily by the electronics industry. Faster microprocessors and faster, larger storage devices allow companies such as Silicon Graphics to develop faster graphics-intensive computers whose increased capabilities permit new and different production possibilities. Distribution clockspeed is also driven by the intense competition for viewers that new channels hope to win.

With respect to changes in clockspeed (the third clockspeed analysis question), although difficult to fathom, far more signs point to a speeding up rather than a slowing down. Widespread availability of powerful computers and the universal access to the Internet may encourage entry into both production and distribution. Just as the Internet and computing technology have powered an explosion of entry into print media, there is every reason to believe that an analogous explosion in video may follow as the costs come down and the number and variety of channels increase. As much as the media moguls try to control the distribution channels to wring maximum value from their franchises, new technologies and a huge potential viewer market should keep up the innovation, entry, and clockspeeds.

With respect to the position of the industry on the double helix (the fourth clockspeed analysis question), as discussed in chapter 2, the industry seems to be integrating,[39] in part because of the desire to hedge uncertainty in the relative future values of the contributions to the different supply chain components. Also, this vertical consolidation by some players has encouraged even more consolidation (by other players) as each production studio moves to assure itself of distribution channels that are not captive to a direct competitor. Perhaps surprisingly, this integrated supply chain structure is accompanied by a highly modular product structure. Virtually every movie production can be delivered on any of the available delivery platforms (for example, network broadcasts, cable, satellite, cable, or movie theaters). This mismatch serves only to amplify the volatility that the industry is likely to see. Little synergy in delivering value to the customer is achieved by the existing vertical media supply chain structures.

In terms of dependency dynamics (the fifth clockspeed analysis question), I think that the field is still wide open. As discussed in chapter 2, any of several possible links in the chain could become the scarce resource. Despite this

[39] "There's No Business Like Show Business," *Fortune*, June 22, 1998, pp. 86-104.

uncertainty, let me suggest another tack by asking what windows of opportunity exist in this industry.

Consider the fraction of movies viewed that involve a trip to the video rental store. To watch a video, the consumer drives to the rental store, chooses a movie, and drives home with it. After watching the movie, this customer has to drive back to the rental store to return the cassette, and then drive home again. The final score: Four automobile trips, one video consumed. (No wonder the oil and automobile industries have been bigger than the movie industry in Hollywood!)

Here, however, we find an open window of opportunity: Who will first find a way to make driving to the video store obsolete? Whoever creates a convenient, efficient, easy-to-use means of accessing the world's video libraries from the home will fill a giant gap in the industry's structure and make a fortune at it. A huge opportunity awaits the right entrepreneurial idea and technology. A clockspeed analysis suggests pointedly, however, that this window of opportunity, great as it appears, may not be open for long.

We see, then, that a mapping of the supply chain can be followed fruitfully by a clockspeed analysis of its elements. We must emphasize that the analyses presented in this section -- namely, that of the Joint Strike Fighter (JSF) technology and the infotainment industry's production and distribution segments -- are intentionally short. The purpose is simply to offer a glimpse into the possibilities of the clockspeed-based capability chain analysis. In the next section, we examine actions that one might take in response to a clockspeed analysis, actions that involve the simultaneous design of products, processes, and the supply chain in order to take the fullest advantage of those three elements in setting a workable strategy for your company. Although advantage is only temporary, there is much to be gained from bringing all elements of one's company in line with those of your entire chain in order to avoid costly delays and setbacks. We call this *three-dimensional concurrent engineering* (3-DCE).

6. Three-Dimensional Concurrent Engineering

6.1 Historical Perspective: Throwing It over the Wall

Prior to the 1980s, in most Western manufacturing companies, the work of marketing, designing, developing, and delivering products proceeded according to a fixed sequence of events, all directed by a bureaucracy of managers, research directors, and technicians. In industries such as consumer electronics and automobiles, where innovation is the watchword, product designers sat in their labs at the top of the hierarchy, developing marvels of technology. They left it to the drudges in manufacturing to figure out how to churn out their inventions in high volumes at costs that would make the manufacturing venture feasible. In its turn, the purchasing department served the needs of manufacturing: The purchasers sought compliant, low-cost suppliers to deliver components or materials to the factories where these new products could be mass-produced.

The operating policy these companies adopted has been called "Throwing it over the Wall." That is, a typical company, much like a medieval castle, constructed protective walls around certain groups, functions, or departments, in effect keeping out people who did not belong. The research laboratory, for instance, was certain to have the highest walls, and only the initiated might enter its sacred chambers. Having invented a new product, these architects of the imagination would toss their designs over the walls of the lab and down to the people in manufacturing, who might well have to guess what the design was for – and then how to make it.

Often oblivious to the realities of the supply chain, these fabricators, in turn, would throw their requirements down to the purchasers, who would scurry around in search of the right commodities and the least expensive suppliers. When discussions did occur between any of these groups, they were haphazard at best; and at worst, relations were deeply acrimonious. The inventors never liked to hear that they had designed products that could hardly be manufactured without costing a fortune. Meanwhile, those who actually built the item would point fingers at the purchasers for not securing the right materials on time. Product manufacturing often fell hopelessly behind schedule.

Further complicating the manufacturability problem, many companies adopted the age-old functional organization structure for their product development. In a typical U.S. or European automobile company, for example, the head of a product development project for a new vehicle would have to "borrow" engineers -- some of whom might be assigned to multiple projects -- from functional departments such as body development, fuel systems, or electronics. These engineers, however, identified primarily with their home departments, not with the project group to which they were temporarily assigned. After all, their rewards and career opportunities came from the heads of those functional departments, not from the ad hoc project managers, who wielded little clout in the great organization scheme.[40]

The disasters in industrial performance such as those of RCA and General Motors have been thoroughly documented. Clark and Fujimoto, for example, survey the severe disadvantages suffered by U.S. and European automotive firms in contrast to the relative success enjoyed by Japanese auto makers.[41] Such woes are further catalogued in numerous other industries in the best-selling *Made in America*,[42] based on industrial performance research conducted over several years at MIT.

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[40] Kim Clark and Takahiro Fujimoto, *Product Development Performance* (Boston: Harvard Business School Press, 1991).

[41] Ibid.

[42] Michael Dertouzos, Richard Lester, and Robert Solow, *Made in America* (Cambridge: MIT Press, 1989).

6.2 *The Power of Concurrent Engineering*

The general malaise in U.S. manufacturing competitiveness in the 1970s and 1980s caused many companies to seek a revitalization by benchmarking successful Japanese companies. Analysis of their innovations in supply chain management, manufacturing, inventory control, and other areas brought to light such concepts as "lean production"[43] and "concurrent engineering."[44] Sometimes referred to as "design for manufacturability" (DFM), concurrent engineering (CE) seeks to improve manufacturing performance not only by making changes, substantive or incremental, at the factory (for instance, installing appropriate automation, streamlining the assembly line), but by coordinating the design of products with the actual production system in the factory. This is, in essence, the principle behind designing a product for manufacturability. Those designers, used to working in isolation behind the walls of their laboratories, would need to have a crash course to learn how better to collaborate with their colleagues in procurement and manufacturing if the company hoped to meet the success of foreign companies that had already mastered the techniques of CE.

Table 6.1 lists some of the key procedures of concurrent engineering.[45]

TABLE 6.1: KEY STEPS IN CONCURRENT ENGINEERING

1. Analyze first the architectural design of both processes and production in order to identify fundamental problems. Then scrutinize the details of the actual design of products and the processes in place to produce them.
2. Break down the product and process systems into their component parts, or subsystems, and identify the interactions within and across them.
3. Align the requirements for the actual design of the product with those for the process design and organizational structure.
4. Explore alternatives for the primary product design process and manufacturing processes.
5. Estimate early the costs of adopting various process options.
6. Estimate early the time requirements -- in person-hours, but especially in the critical path time effects -- of executing different design options.

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[43] Jim Womack, Daniel Jones, and Daniel Roos, *The Machine That Changed the World: The Story of Lean Production* (New York: HarperPerennial Library, 1991).

[44] See, for example, James Nevins and Daniel Whitney, *Concurrent Design of Products and Processes: A Strategy for the Next Generation in Manufacturing* (New York: McGraw-Hill, 1989); K. Ulrich and S. Eppinger, *Product Design and Development* (New York: McGraw-Hill, 1994); Mitchell Fleischer and Jeffrey Liker, *Concurrent Engineering Effectiveness* (Cincinnati: Hanser Gardner Publications, 1997).

[45] For the most part, these principles are well described by Nevins and Whitney, *Concurrent Design of Products and Processes*, and by Ulrich and Eppinger, *Product Design and Development.*

7. Identify and alleviate any bottlenecks in the CE process.
8. Manage the design process with multi-functional teams, working concurrently.
9. Align incentives for design such that tradeoffs associated with selection of alternative design options will be made from a global, product life cycle perspective.

Concurrent engineering is a model technique for a fast-clockspeed world. When companies have little competitive pressure and slowly evolving technologies, the burden of time weighs relatively lightly. In the absence of time pressure, the penalties for working slowly and sequentially rather than concurrently -- and for iteration and reworking -- are mild. As the clockspeed of industry after industry began to heat up from the driver of global competition, the necessity of concurrency struck home.

Although concurrent engineering of product and process led to great improvement in performance in the 1980s and early 1990s, those tools no longer provide significant *differential* advantage in many industries.[46] A significant number of the most competitive companies have already adopted standard CE methodology. The best of them are now seeking to master the next leap in process capability -- namely, three-dimensional concurrent engineering (3-DCE).

6.3 Concurrent Engineering in Three Dimensions

If the traditional two dimensions of CE are insufficient to ensure competitive advantage, what must be added to bring the theoretical model in line with current and future market realities? The answer to this question lies in the design and development of the supply chain. Of course, many companies already make significant efforts in designing their supply chains. Often they do so, however, without full corporate consciousness of the strategic issues at stake or of the opportunities available to them if they were to focus on designing the supply chains strategically and concurrently with their products and production processes. In short, supply chain issues are hardly newcomers to manufacturing and design processes, but in the traditional way of considering concurrent engineering, many companies have treated development of the supply chain as an afterthought.

When firms do not explicitly acknowledge and manage supply chain design and engineering as a concurrent activity to product and process design and engineering, they often encounter problems late in product development, or with manufacturing launch, logistical support, quality control, and production costs. In addition, they run the risk of losing control of their business destiny.

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[46] For evidence on the first assertion, see Kim Clark and Takahiro Fujimoto, *Product Development Performance* (Boston: Harvard Business School Press, 1991). For evidence on the second, see David Ellison, Kim Clark, Takahiro Fujimoto, and Young-Suk Hyun, "Product Development Performance in the Auto Industry: 1990s Update," working paper 95-066, Harvard Business School, 1995.

Supply chain design has particular importance when the effects of the chain relationship are long-lasting. This occurs especially when the competitive impact of supply chain design and development decisions extend over several generations. Even the most innocuous decision affecting supply chain designs can have enormous ramifications extending all the way to the continued survival of a company or an entire industry. In the personal computer industry, for instance, IBM's supply chain design practically handed over the reins of the industry to Microsoft and Intel. Although IBM has regained some of the ground it lost, it occupies only a spit of land that it might have controlled if the company had taken a three-dimensional view of concurrent engineering. Its failure to do so represents a decision that changed the course of the world's computer industry.

6.4 Architectures in 3-D: Product, Process, and Supply Chain

In section 4 we saw the double helix partly through the lens of product architectures. As these evolved from integral to modular and back to integral again, we saw synchronization with the evolution of the industry and supply chain structures, which themselves modulated from vertical to horizontal and back to vertical again. To approach three-dimensional concurrent engineering, we can again stand at the level of architecture, but this time examine it in three dimensions represented by products, processes, and supply chains.

Analyzing product and process design problems at the architecture level provides a strategic, high-level perspective on how supply chain design can be integrated into concurrent engineering. In a seminal paper, Karl Ulrich describes product architecture as the scheme by which the function of a product is allocated to its constituent components.[47] He distinguishes between integral and modular product architectures, a distinction that is fundamental to three-dimensional concurrent engineering.

To understand these concepts, think of integral architectures as exhibiting close coupling among the elements of the product. An integral product architecture might feature, for example,

- Components that perform many functions
- Components that are in close proximity or close spatial relationship
- Components that are tightly synchronized.

In contrast, a modular architecture features separation among a system's constituent parts, whereby,

- Components are interchangeable

[47] Karl Ulrich, "The Role of Product Architecture in the Manufacturing Firm," *Research Policy* 24 (1995): 419-40.

- Components are individually upgradable
- Component interfaces are
- System failures can be localized.

Applying these distinctions, we would expect to see integral architecture products with principal components having multiple functions. Engineers call this "function sharing."[48] For example, consider the very simple product of a carpenter's hammer. The claw head of this everyday tool typically exhibits an integral architecture. The steel head, a single component, performs two distinct functions: The head end drives nails, whereas the "claw" removes them.

A more complex example is the wing structure of a typical commercial jet airplane such as the Boeing 777. The wing must be designed and constructed to perform (at least) two functions: It must provide lift to the aircraft, and it must serve as a hollow tank for storing jet fuel.

An equally intricate example is the frame of a modern motorcycle, such as a model built by Honda.[49] In contrast to an automobile, which has separate body, engine, and gasoline tank components, motorcycles have a complex frame structure that integrates structural body functions with engine and gas tank components.

Products also exhibit characteristics of an integral architecture if some of their functional requirements must be delivered by various subsystems and cannot be reduced to a single component or subsystem. For example, automobiles and airplanes have stringent requirements for total weight, a functional requirement that spans virtually all of their subsystems (such as chassis, fuel consumption, exhaust, braking, to name a few). Similarly, mainframe computers require that the enormous amount of heat generated by key components be eliminated; otherwise, the system runs the risk of becoming damaged.[50]

Modular architecture products, in contrast, exhibit interchangeable components, each of which has a single or only a few functions. One common example is a home stereo system, for which customers mix and match receivers, speakers, compact disk players, and other components, often from different manufacturers. This mix-and-match convenience is now possible because the interfaces across those components have been standardized throughout the industry. Desktop personal computers, with their motherboards, disk drives, DRAM chips, modems, monitors, and keyboards are also highly modular.

In contrast to motorcycles, for instance, most modern bicycles (as discussed in section 4) are also highly modular. Manufacturers now build frames that can

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[48] Ibid.

[49] This example is given by Ulrich.

[50] For a thorough discussion of the theory and application of product architecture, see Timothy W Cunningham, "Chains of Function Delivery: A Role for Product Architecture in Concept Design," unpublished dissertation, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Mass., 1998; Timothy W. Cunningham and Daniel E. Whitney, "The Chain Metrics Method for Identifying Integration Risk during Concept Design," working paper, MIT Center for Technology Policy and Industrial Development, Cambridge, Mass., 1998.

accommodate a wide variety of interchangeable components such as seats, brakes, chains, freewheels, and gear shifters from a multitude of suppliers.

6.5 The Concept of Supply Chain Architecture

Building on the product architecture concept enables development of the construct of supply chain architecture, a richer concept than that of traditional make/buy or vertical integration, which focuses primarily on the ownership of assets in the supply chain.[51] The supply chain architecture concept is one of the keys to a deeper analysis of the make/buy challenge. This concept also is essential in extending the integral-modular distinction from products to supply chains. An integral supply-chain architecture features close *proximity* among its elements. Proximity is measured along four dimensions: geographic, organizational, cultural, and electronic.[52]

Geographic proximity can most simply be measured by physical distance. Although electronic communication technologies have reduced in many cases the importance of geography, for many other product and process engineering projects, geography significantly affects the project outcome. Especially for highly integral product designs, continuous iteration among design parameters for key interrelated subsystems are most efficiently handled by co-located (essentially integrated) engineering teams.

Measuring *organizational* proximity is a bit more complex, but can be approximated by constructs of ownership, managerial control, and interpersonal and inter-team dependencies. Thus, a customer and supplier who are owned within the same corporate structure have interlocking corporate ownership, report to the same general manager or CEO, and have tightly interconnected work processes among functions or teams. They can usefully be described as having close organizational proximity.

Cultural proximity captures commonality of language, business mores, ethical standards, and laws, among other things. Matsushita Electric Corporation exemplifies a global company with a well-established value system and philosophy, which was enunciated by the company's founder, the late Kenoske Matsushita. Even today, those values continue to motivate and direct Matsushita employees and company policies.

Finally, *electronic* proximity, or what today might be termed a "virtual vicinity," can be captured through email, electronic data exchange (EDI), video

[51] See, for example, Sharon Novak, "Sourcing by Design : Product Architecture and the Supply Chain," working paper, Massachusetts Institute of Technology, Cambridge, Mass., 1998. This paper presents data from the auto industry to suggest that supply chain integration is a significant variable in explaining performance in the auto industry, whereas traditional vertical integration is not significant.

[52] To my knowledge, these dimensions of supply chain proximity are first mentioned in Charles Fine, George Gilboy, Kenneth Oye, and Geoffrey Parker, "The Role of Proximity in Automotive Technology Supply Chain Development: An Introductory Essay," working paper, Massachusetts Institute of Technology, Cambridge, Mass., May, 1995. The paper is available at http://imvp.mit.edu/imvpfree/Fine/proximty.pdf.

conferencing, and other technologies among members of the supply chain. Both Ford Motor Company[53] and Toyota,[54] as examples, have invested significantly in computer-aided design software that can be used across the supply chain for 3-D concurrent engineering, fostering electronic proximity within the supply chain.

A supply chain with a high degree of integrality, therefore, is one in which a manufacturer and its principal suppliers are concentrated in one city or geographic region, have common or interlocking ownership, share a common business and social culture, and are linked electronically. Excluding the last of these dimensions, the well-known "lean production system"[55] was developed within a highly integral supply chain. This highly respected and widely imitated system was conceived and nurtured by Toyota Motor Corporation in the Nagoya/Toyota City industrial region within a highly uniform culture and with significant ownership and managerial participation by Toyota in its suppliers.

Interestingly, Toyota's early efforts at integrating North American suppliers into a global product development extension of its Toyota City model met numerous difficulties.[56] That is, even the widely respected Toyota struggled when it tried to implement *global* three-dimensional concurrent engineering from a highly integral supply base. Toyota's solution to these problems featured a dramatic improvement in electronic proximity with sophisticated CAD (computer-aided design) tools shared across a network between engineers in Toyota-Japan and its North American suppliers.

In contrast to the integral system, a modular supply chain exhibits low proximity along most or all of the dimensions listed above. That is, modular supply chains are those that may well exist over a huge expanse of geographical territory and have autonomous managerial and ownership structures, diverse cultures, with low levels of electronic connectivity. Of course, extremely low levels of proximity in all these dimensions would render a supply chain unmanageable in a fast- or even moderate-clockspeed industry, so some degree of close proximity along one or more of these dimensions is necessary for survival in most cases. If you do not have high geographic, organizational, or cultural proximity, then you probably need significant electronic proximity to coordinate a globally-distributed chain, like that of the merged DaimlerChrysler organization combined with its acquired Nissan Truck operation, for example.

We can still observe significant differences, however, in the extent of proximity across successful supply chains today. Modular supply chains tend to

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[53] Jared Judson, "Integrating Supplier Designed Components into a Semi-automatic Product Development Environment," Massachusetts Institute of Technology, LFM Master's Thesis, 1998; idem, "Assessing a New Product Development Process Using 3-Dimensional Concurrent Engineering," term paper for Course 15.769, Massachusetts Institute of Technology, Cambridge, Mass., 1998.

[54] Christopher Couch, "Power in the Chain," working paper, Massachusetts Institute of Technology, Sloan School, Cambridge, Mass., October, 1997.

[55] Womack et al.

[56] Christopher Couch, "Power in the Chain," working paper, Sloan School, Massachusetts Institute of Technology, Cambridge, Mass., 1997.

feature multiple, interchangeable suppliers for key components. As one example, consider the personal computer industry. The supply chains for these devices are widely dispersed across myriad companies, primarily in North America and Asia. Those companies -- including semiconductor fabricators, circuit board assemblers, modem manufacturers, disk drive makers, and software houses -- are located in the United States, Japan, Taiwan, Singapore, Malaysia, Thailand, China, India, and many other countries. They share neither geographic, nor organizational, nor cultural proximity. Only the advent of technologies for electronic proximity -- e-mail, faxes, intranets, electronic data interchange (EDI), and videoconferencing, for example -- has allowed these highly modular supply chains to thrive.

In contrast to that of Toyota City, the supply network resulting from the "global sourcing" policies of General Motors has retained significant component development, manufacturing, and integration capabilities internal to the corporate entity. These internal capabilities enable GM to treat many of its suppliers as interchangeable to some degree and to outsource components in a competitive bidding mode while the company does the integration work itself. This policy has resulted in a collection of suppliers that are widely dispersed geographically, organizationally, and culturally, even for a fairly integral product such as an automobile.

A complex of a different sort is offered by the garment manufacturing industry in Italy.[57] This industry comprises hundreds of small firms, many of which specialize in just one step of the garment-producing supply chain. That is, a firm might concentrate on designing, spinning, weaving, dyeing, cutting, or sewing, rather than on trying to perform all of these steps. Members of this supply chain, although they often share geographical and cultural proximity, still exhibit modular characteristics of interchangeability.

Finally, consider the example of telecommunications services. Although the U.S. system was developed by a highly integrated "Ma Bell" in the middle of the twentieth century, by the 1990s, partly as a result of the historic spin-off of the local service providers ("Baby Bells") in 1984, the industry structure evolved. Consumers now build their own supply chains, choosing separately the interchangeable suppliers of telephone handsets and hardware, local service, long distance service, cellular service, repair service, Internet access, and the like. This evolution shows another instance of movement along the double helix and reinforces that we ought to expect to see significant variety in the supply chain architectures of different industries.

[57] Italy's garment manufacturing industry has been studied extensively by business academicians, including Michael Porter, *The Competitive Advantage of Nations* (New York: Free Press, 1990); Michael Piore and Charles Sabel, *The Second Industrial Divide* (New York: Basic Books, 1984); and Richard Locke, *Remaking the Italian Economy: Local Politics and Industrial Change in Contemporary Italy* (Ithaca: Cornell University Press, 1995).

6.6 Concurrent Design of Product and Supply Chain Architectures

Before integrating the complexities of process architecture into this discussion, let us consider the relationship between product architecture and supply chain architecture as discussed above. To a significant degree, product and supply chain architectures tend to be aligned along the integrality-modularity spectrum. That is, integral products tend to be developed and built by integral supply chains, whereas modular products tend to be designed and built by modular supply chains.

In essence, product and supply chain architectures tend to be mutually reinforcing. As we saw in section 4, the Chrysler Corporation helped insure its survival by taking the extraordinary step (extraordinary for Detroit auto makers) of modularizing its product design and its supply chain to offer suppliers greater autonomy and the potential for increased revenues.

In the case of the personal computer industry, modularity in product architecture enables manufacturers to use modular supply chains. By extension, the existence of a strong modular supply chain encourages the further development and use of modular products, as evidenced by Compaq, Dell, and other makers of personal computers. Similarly, the more complex the development process for integral products, the higher degree of integration we can expect in integral supply chains. This effect results from the intensive, iterative communication required for development, as exemplified by the companies that produce aircraft for defense purposes. Fighter jets comprise highly integrated subsystems that are extremely difficult (if not impossible) to decompose into independent modules for outsourcing to highly independent suppliers.[58]

[58] Cunningham, "Chains of Function Delivery."

These relationships are illustrated in fig. 6.1.

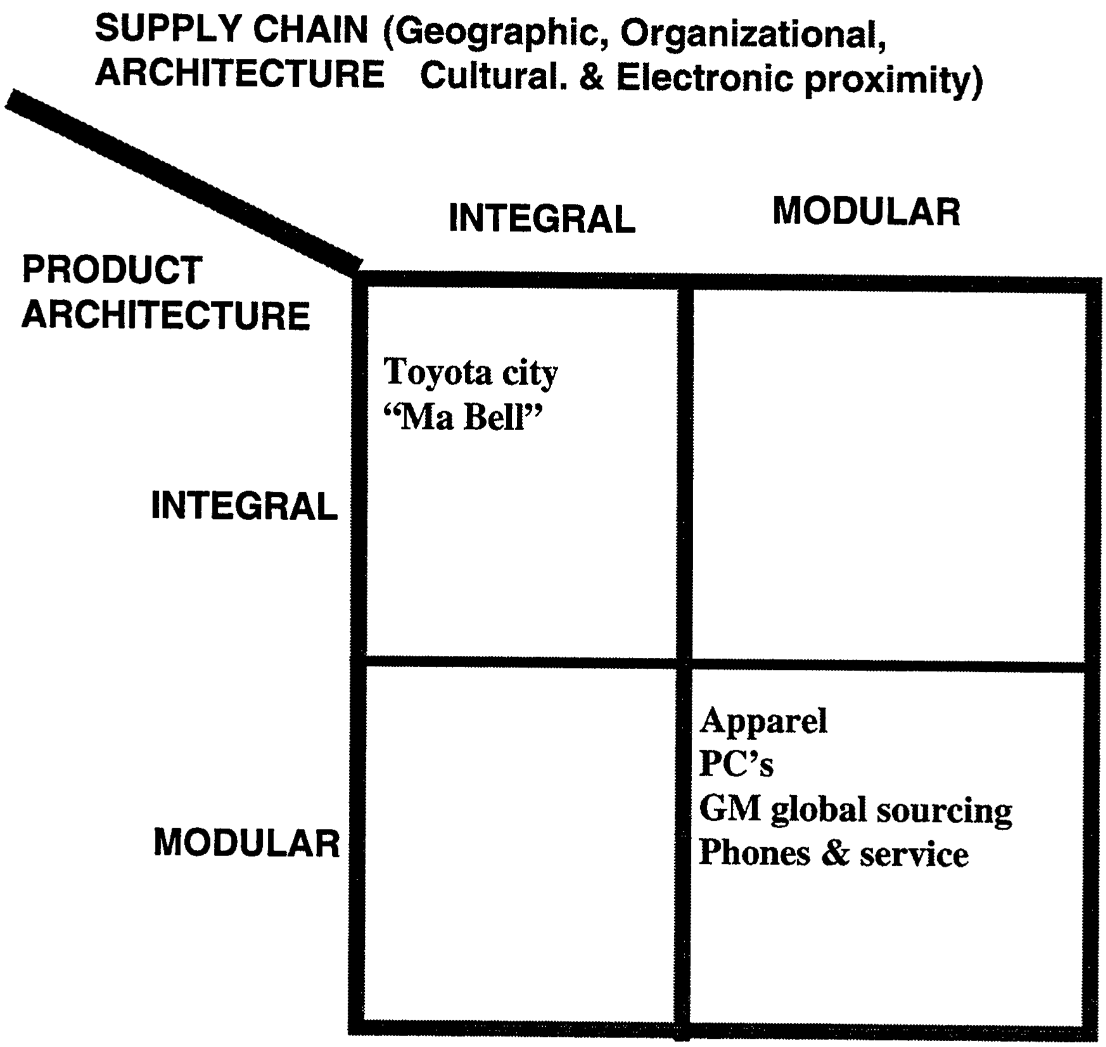

Fig. 6.1. The Interaction Effects between Product and Supply Chain Architectures

Fig 6.1 illustrates the cases of our discussion so far. Toyota automobiles in Toyota City, as well as telephone systems in the mid-twentieth century zenith of "Ma Bell," were both examples of integral products provided by integral supply chains. At the other end of the spectrum, modularity in product design enables the modular supply chains of apparel design and manufacture, General Motors' global sourcing, personal computers, and 1990s telephone service.

Now, consider an off-diagonal example. BMW products are among the highest performance luxury sedans in the world. In its product development process, BMW will sacrifice much in cost and development time in order to create a vehicle that will thrill customers -- many of whom are sophisticated automobile enthusiasts – and deliver the best possible acceleration, braking, handling, and the like. To achieve this high level of product performance, BMW has historically crafted a highly integral vehicle design, relying on an integral supply chain centered in the Munich area, around the company's corporate headquarters. This high level of integrality assures tight control of all vehicle specifications and process interactions among all key subsystems.

In the early 1990s when BMW decided to build a factory in the United States, the company also chose (reputedly under some pressure from local governments) to use a number of American suppliers instead of bringing all of its German suppliers to the North American site. To the company's chagrin, BMW engineers discovered that some of their American suppliers, although highly skilled in working with their traditional American customers, were ill-equipped for the highly integral and iterative product development and launch processes that were second nature to the skilled craftsmen in the German supply base. As a result, BMW's first U.S. manufacturing process experienced delays and a costly launch, when the company and its suppliers scrambled to reengineer the modular supply base to meet the demands of BMW's integral vehicle designs.[59]

6.6.1 Process Architecture

Like the architectures for the product and supply chain, it can also be useful to locate your process architecture along the line extending from the extremes of vertical-integral and horizontal-modular. Whereas we used four dimensions (geographic, organizational, cultural, and electronic) to characterize the degree of integrality and modularity in the supply chain architecture, for process architecture we use only two dimensions: time and space. That is, process architectures can be integrated in both time and space (highly integral), integrated in either space or time, or dispersed in both space and time (highly modular). For example, a significant portion of the developed world's just-in-time production efforts of the past two decades has been devoted to reducing or eliminating time dispersion in productions systems. Nevertheless, one can still observe differences along this dimension, although the variance is far smaller than that of twenty years ago.

To illustrate the concept, consider the following examples in fig. 6.2:

[59] Novak.

TIME \ SPACE	Tight/Integral	Loose/Modular
Tight, Integral, Fast	Dell Computer Assembly	Newspaper Production
Dispersed, Modular, Slow	Wine Making	Non-emergency Health Care

Fig. 6.2. Different Process Architectures along the Dimensions of Time and Space

As we saw in section 5, Dell Computer Corporation's computer assembly process is very tightly integrated in time. An entire computer is built in a few hours to be rushed off to its future owner. Dell's assembly process is tightly-integrated in space as well. All assembly operations take place in a single work cell in a single factory operated by a very small team.

Contrast this process with newspaper production such as we might find at the *Wall Street Journal*, for example. Journalists adhere to a tight schedule, usually a 24-hour deadline for product completion, but the reporters contributing to the product are highly dispersed geographically as are the printing presses on which the product is run. Another example in this category is software development. A software company can implement full assembly and testing of a product prototype once every 24 hours if it wishes, even though the software engineers may work in dispersed facilities across several continents.

In the opposite quadrant of the space and time dimensions, premium-brand wine making serves as an example of a process that requires an extended time component. The fermentation process often extends many years, whereas most of the work -- growing, picking, processing, fermenting, and aging -- occurs in a single location, the winery.

Finally, services such as non-emergency health care tend to be spread out geographically -- for example, in a large hospital complex or across multiple facilities within a large city. These services often span months or years, depending on the ailment being treated. (Emergency care, on the other hand, tends to be very tight both in time and in space.)

Some apparel making, in addition, is widely dispersed in both time and space. For example, the ski-wear maker Sport Obermeyer has a production system that spans the Pacific Ocean and requires several months for product completion.[60]

6.7 The Imperative of Concurrency

Fig. 6.3 illustrates several interactions across product, process, and supply chain development activities. Where the three ovals overlap we locate those activities that need to be undertaken concurrently, either bilaterally or collectively, among the three functions. This diagram further illustrates that not all of the activities undertaken within any of the three functions need to be performed in conjunction with members of the other groups. That is, not all work must take place in "integrated product teams" (IPTs). Rather, IPTs would concern themselves only with tasks where activities of two or all three functions overlap.

[60] Janice Hammond and Ananth Raman, *Sport Obermeyer, Ltd.* Case Study #N9-695-022, (Boston: Harvard Business School Publishing, 1994); Marshall Fisher, et al, "Making Supply Meet Demand in an Uncertain World," *Harvard Business Review*, May-June, 1994, Vol. 72, pp. 83-93.

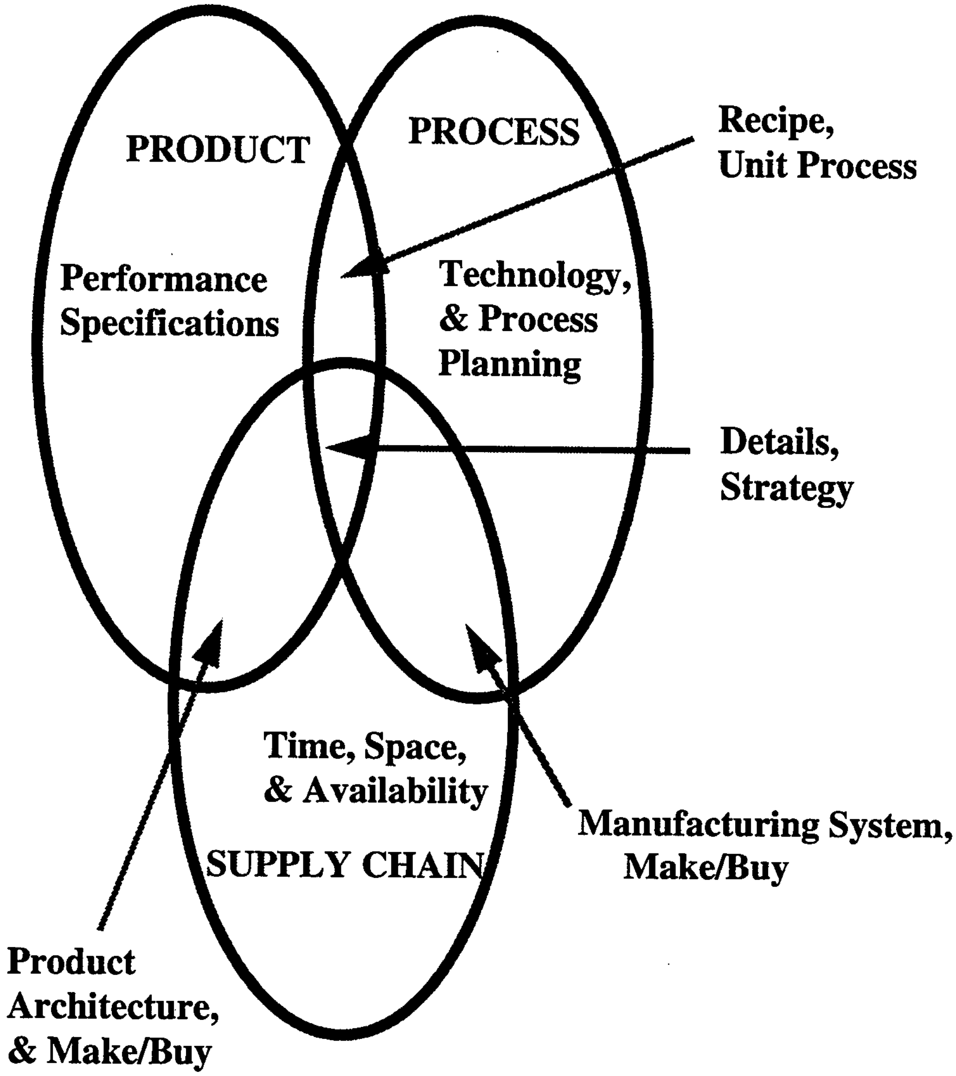

Fig. 6.3. Overlapping Responsibilities across Product, Process, and Supply Chain Development Activities.

Figure 6.3 attempts to capture visually many of the ideas in 3-DCE. One can consider how architecture decisions are made through discussions within and across the product, process, and supply chain organizations. In addition, many of the tools -- for make/buy decisions and product development, as examples, -- discussed in the following two chapters can be placed within the framework of this diagram.

A further refinement of the overlapping areas of concurrency across product, process, and supply chain development appears in fig. 6.4, which also highlights the imperative of concurrency. This figure divides each of the three developmental areas -- product, process, and supply chain -- into two subactivities:

- *Product development* is subdivided into activities of architectural choices (for example, integrality vs. modularity decisions) and detailed design choices (for example, performance and functional specifications for the detailed product design).

- *Process development* is divided into the development of unit processes (that is, the process technologies and equipment to be used) and manufacturing systems development -- decisions about plant and operations systems design and layout (for instance, process/job shop focus vs. product/cellular focus).
- *Supply chain development* is divided into the supply chain architecture decisions and logistics/coordination system decisions. Supply chain architecture decisions include decisions on whether to make or buy a component, sourcing decisions (for example, choosing which companies to include in the supply chain), and contracting decisions (such as structuring the relationships among the supply chain members). Logistics and coordination decisions include the inventory, delivery, and information systems to support ongoing operation of the supply chain.

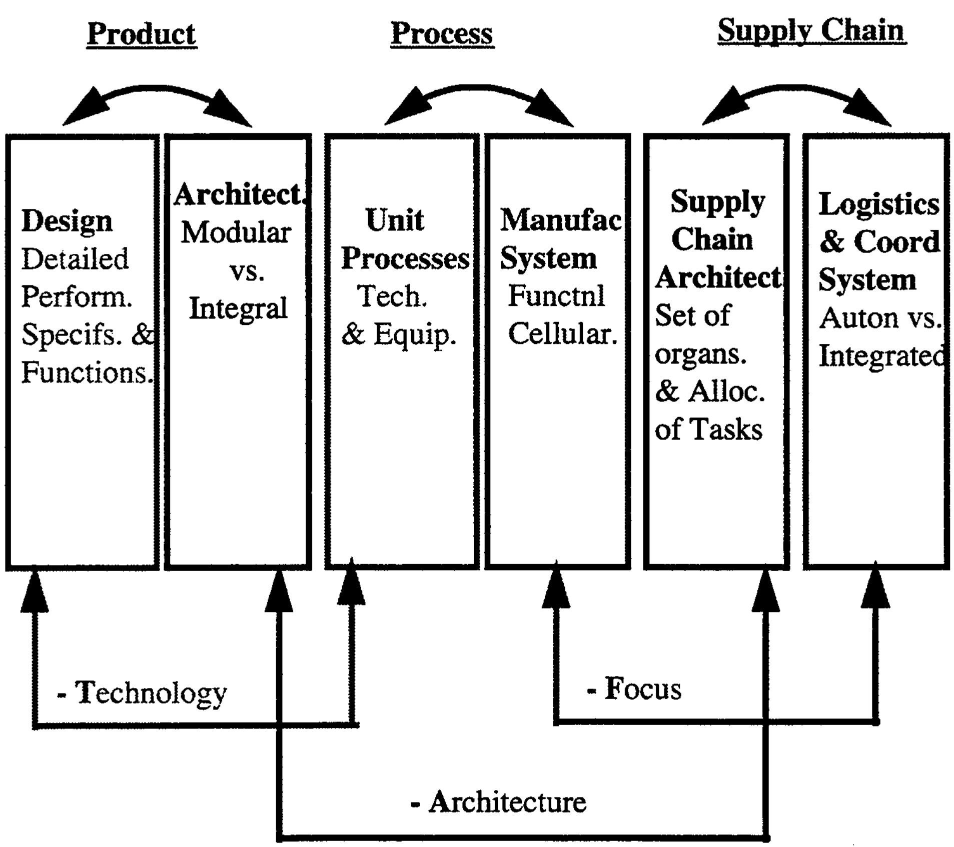

Fig. 6.4. The "FAT 3-DCE Decision Model"

For purposes of this chapter, the most important aspect of fig. 8.4 is the series of overlapping arrows at the bottom of the chart. These arrows highlight the linkages across the three activities, emphasizing where concurrent development takes on paramount importance. Three of these bilateral links are emphasized. We call them, respectively: Focus, Architecture, and Technology (FAT).

The Architecture link was discussed above, in the context of fig. 6.2 -- aligning product and supply chain architectures. The Technology link encompasses the coordination of detailed product designs with process capabilities, which is the domain of traditional (two-dimensional) concurrent engineering.

Focus decisions link choices about the manufacturing system design with those in logistics and materials system design. Since the supply chain logistics management system is typically an extension of the in-house manufacturing system design, these process and supply chain design areas are often tightly linked. An important set of decisions in the domain of process design is the extent to which the manufacturing system is "process focused" or "product focused."[61] Traditional job shops and semiconductor fabrication plants tend to be process focused, grouping together all like sets of equipment and unit processes. Concurrently, as the supply chain logistics and materials system is designed, managers must make decisions about the chain management system. For instance, should it be tightly integrated as Dell's is, or should it remain a loose-knit group of autonomous system suppliers as we find in the manufacture of defense aircraft?

The next four cases, from Intel, Chrysler, Toyota, and Boeing, further illustrate these ideas.

6.8 Four Case Examples: Intel, Chrysler, Toyota, & Boeing

Intel

In an era and industry of unprecedented clockspeed acceleration, Intel Corporation has risen about as quickly as any corporation in history as a major manufacturer. Most of Intel's growth to a $25 billion corporation occurred over less than a decade, a period during which the company built highly capital-intensive factories and introduced new products at a blistering pace. Much of its success in keeping competitors at bay during the period of explosive growth resulted from the ability to execute new product and process development with many new suppliers at breakneck speed. In short, Intel proved to be a master of fast-clockspeed 3-DCE.

Given the complexity of the underlying technologies, we can gain a valuable understanding of how Intel simplified the daunting 3-DCE challenges it faced. Its approach offers lessons for any company contemplating a shift to three-dimensional concurrent engineering. Intel's microprocessor product families -- popularly known

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[61] Robert H. Hayes and Roger Schmenner, "How Should You Organize Manufacturing," *Harvard Business Review*, January-February, 1978, Vol. 56, pp. 105-118.

as the 286, 386, 486, and Pentium processors -- resulted from a massive product development process, involving hundreds of engineers and scientists working over multiple sites and multiple years.[62]

Historically in the semiconductor industry, where DRAM (dynamic random access memory) products absorbed the lion's share of new investment, each new generation of product -- 64Kb RAM, 256Kb RAM, 1Mb RAM, and so forth -- each product launch occurred on an all-new generation of manufacturing process (typically denoted by the smallest line-width on the integrated circuits). Thus, for a DRAM manufacturer, launching a new product meant simultaneously launching a new process -- always a complex affair. Through most of the 1980s, the Japanese semiconductor companies concentrated on DRAM design and production, exploiting their skills in precision clean manufacturing. The Japanese tended to be the process technology leaders into each new smaller line-width process generation.

By the early 1990s, however, Intel found itself in the position of needing new processes (for example, more metallization layers) in advance of the DRAM industry's needs or its willingness to invest in such processes. As a result, the DRAM makers no longer unequivocally drove process development. Having emerged as the 800-pound gorilla of the industry in the early 1990s, Intel had to learn to be a process technology leader and to develop systems whereby it could continue to improve process technology while accelerating its pace of product development.

Intel crafted a brilliant 3-DCE strategy that used product/process modularity to reduce significantly the complexity of the company's technical challenge: Throughout the 1990s, the company launched each new microprocessor generation on the "platform" of an old (line-width) process. Alternately, each new process generation was launched with an "old" product technology. For instance, Intel introduced its i486 chip on the one-micron process developed for the i386 chip, a process that had already been debugged. Following the success of this process, Intel created the .8-micron process, which was first tried on the now-proven i486 chip. Next, it launched the Pentium chip on the proven .8-micron process before moving it over to the new .6-micron process. Leveraging this system of alternating product and process launches, Intel created almost perfect modularity between product and process, a marriage that reduced dramatically the complexity of any given launch. Reducing the complexity of concurrent engineering has, of course, been one of the keys to Intel's success in its hyperfast-clockspeed industry.

When viewed through the lens of the third dimension, however, Intel's link between process and supply chain is much more integral. That is, process development goes hand in glove with supply chain development. Especially by the mid-1990s, when Intel needed to drive new process technologies rather than adapt technologies that had already been pretty much debugged by the DRAM manufacturers, Intel found itself nurturing start-up companies that were just

[62] Sean Osborne, *Product Development Cycle Time Characterization Through Modeling of Process Iteration*, MS thesis, MIT-LFM program, 1993.

developing the advanced technologies necessary for the next-generation processes Intel needed. As a result, Intel fostered integral development of new processes and new suppliers to support those processes.[63]

Chrysler

In section 4, we saw that Chrysler of the 1990s could be likened to Compaq of the 1980s. Through a modular product and supply chain strategy, each company managed to upset the advantages of much larger rivals and to trigger a chain reaction of events capable of altering dramatically the structure of the entire industry. In the case of Compaq and the fast-clockspeed computer industry, this series of events is already history. In the slower-clockspeed automobile sector, events are still unfolding before our eyes. In particular, the automobile is not as modular as the personal computer, and neither is the supply chain associated with the car industry.

Through the lens of 3-DCE, we can see both the strengths and potential weaknesses of Chrysler's strategy more clearly: By outsourcing the development and integration of numerous automotive subsystems, Chrysler cut dramatically the total time and cost required to develop and launch a new vehicle. The company has effectively exploited the opportunities from this approach, as described earlier. However, in executing this strategy of modularizing the product and the corresponding sectors of its supply chain, Chrysler seemingly subordinated its relative emphasis on process development, somewhat to the detriment of overall vehicle system features such as reliability.[64]

Because Chrysler, in contrast to many of its competitors, is so quick from concept to car, the company has enjoyed a high rating with consumers on the most desirable designs and features. Such designs have allowed Chrysler to charge premium prices with minimal rebating in the first several years of the 1990s. However, while earning a premium on its designs, Chrysler perhaps lost some ground over customer dissatisfaction with the vehicles' reliability. These, of course, are features that cannot be outsourced to suppliers. Rather, they are inherent in the overall systems engineering of the vehicle.[65]

To build on its early-1990s recovery, perhaps Chrysler will have to reinvest some of its bounteous profits into deeper 3-D systems integration skills, particularly in integrating the process development activities with the advantages the company has already gained through its system of product-supply chain modularity. This

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[63] I am indebted to Randy Bollig, Intel's director of corporate capital acquisition, for these insights into Intel's supplier development system.

[64] "Reliability of Used Cars," *Consumer Reports*, April, 1998, p. 74.

[65] Daniel Whitney, "Identifying Integration Risk during Concept Design," presentation to the MIT Symposium on Technology Supply Chains, May 13, 1998, observed vividly that integral characteristics, like vehicle reliability and NVH (noise, vibration, and harshness) cannot be outsourced to a relibility or NVH supplier. None exist.

system is so well executed that it has been christened the "new American *keiretsu*,"[66] drawing an analogy to Toyota's effective use of outsourced subsystem development. Toyota's systems integration skills and core technology capabilities, however, are very deep. Toyota has outsourced manufacturing capacity, but rarely the fundamental knowledge, a topic discussed in chapter 9.[67]

With the acquisition by Daimler-Benz, Chrysler gains a partner with some of the deepest systems engineering skills in the automotive industry. In the best of all possible worlds, the new Daimler-Chrysler will excel at both the cost-reducing, speed-enhancing modularization of product and supply chain and the quality–enhancing process integration capabilities that provide the true test of a vehicle engineering team's capabilities.

Toyota

As we have seen, Toyota Motor Corporation brilliantly exploited its highly integral Nagoya/Toyota City supply chain in developing its famed lean production system. Furthermore, when Toyota began globalizing its production -- to NUMMI in California and to Georgetown in Kentucky, for example -- the gold standard that the company had established for quality production systems seemed to be exportable without a hitch.

However, globalizing the entire Toyota system of 3-DCE has not gone nearly as smoothly.[68] In their early launch experiences, Toyota's North American suppliers under-performed dramatically relative to Toyota's Japanese suppliers in the entire development process: in quality, cost cutting, and on-time development. These supply chain snafus delayed by as many as ten months the launch of Toyota's North American Camry and Avalon vehicles and raised the development costs by as much as 40 percent.[69] Furthermore, for some critical parts, Toyota took the unprecedented step of arranging for backup suppliers in Japan whose rush-shipment air freight costs to North America sometimes topped $1 million per month.[70] These problems resulted primarily from the relative inexperience of North American suppliers with the Toyota production engineering system, as well as the communication complexity of involving Toyota's Japanese and North American engineering organizations with a complex set of suppliers in both Japan and North America.[71]

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[66] Jeffrey Dyer, "How Chrysler created an American Keiretsu," *Harvard Business Review* 74.4 (1996): 42-56.

[67] Charles Fine and D. Whitney, "Is the Make/Buy Decision Process a Core Competence?" working paper, Massachusetts Institute of Technology, International Motor Vehicle Program, Cambridge, Mass., 1996.

[68] Christopher Couch, "Power in the Chain," working paper, Massachusetts Institute of Technology, Sloan School, Cambridge, Mass., October, 1997. This case example and the associated data and references are taken from this paper.

[69] Ibid., p. 18.

[70] Ibid.

[71] Ibid., pp. 37-40.

Because the Toyota system is built on dense communication links across the entire supply network, adding more nodes for each development step exponentially increased the number of communication channels used. This added complexity of global 3-DCE has led to a more complex overall process. As mentioned, Toyota is investing in improved electronic media to bridge this communication bottleneck, but only time will tell whether Toyota will be the world-class benchmark in *global* 3-DCE the way its lean production system was for integral *local* 3-D concurrent engineering.

Boeing

The aircraft industry has long been one of the turtles of the manufacturing sector. Its development cycles are long; its product lives are long; its processes are long-lasting, as are its supply chain relationships. When a company such as Boeing makes a decision about a supplier or an airplane design, it has to live with that decision for years, if not decades. As a result, when Boeing develops a new airplane (something that only happens perhaps twice a decade), it tends to get representatives from each of product, process, and supply chain involved and talking with each other at a fairly early stage. This is how 3-DCE is supposed to work – at least in a slow-clockspeed world. I call this *static 3-DCE*.

In a fast-clockspeed world, the challenges are significantly more difficult. In such settings, firms need to practice *dynamic 3-DCE*. So, what's the difference? In *dynamic 3-DCE*, the three-dimensional team tasked with developing the product, process, and supply chain for the current airplane project (or whatever product) not only needs to focus on the enormous complexity of the current project, but also must consider the impact of the decisions the team makes on the developers of future projects. In particular, how do these decisions affect the set of competencies the firm will have mastery over once the project is completed? What kind of dependencies on which other members of the value chain will result from the choices made on the current project?

These issues take us out of the realm of the theoretical and into that of practical applications. In the final sections of this report, we will see how the theoretical notions of fruit fly industries, capability (supply) chains, and the fluctuation along the double helix between the vertical structure (with its reliance on integrated products) and the horizontal structure (which features modular products) can help companies make both short- and long-term business decisions

7. Tools for Three-Dimensional Concurrent Engineering

Stimulated by the success of superior Japanese manufacturing methods, many Western manufacturers in the 1980s worked overtime to benchmark remarkable companies such as Toyota and Sony. By the early 1990s, many had achieved a huge breakthrough in their understanding of competitive advantage through manufacturing. A large portion of the learning came under the heading of concurrent engineering (CE) or design for manufacturing (DFM). Managers realized that they could not achieve improved manufacturing performance solely, or even primarily, by concentrating on the factory; rather, they had to focus on concurrently designing the product and the manufacturing process -- that is, designing the product for manufacturability.

Three-dimensional concurrent engineering (3-DCE) extends this concept from products and manufacturing to the concurrent design and development of capabilities chains. As discussed in chapter 8, product development, manufacturing, and supply chain management have traditionally been thought of as separate business processes. Some companies still think of them this way. I recently attended a briefing by a senior executive of a Fortune 50 manufacturing company who stated that management had decreed that the corporation had four core business processes, among which were product development and supply chain management.

Such statements -- and the implicit thinking that about strategy that goes with them -- make me uneasy. By declaring each a "core business process," management appears to have decided to separate product development and supply chain development. As I have argued in this book, however, 3-D concurrent engineering should be treated, both conceptually and operationally, as a *single, integrated capability,* rather than as three separate functions, one each for products, processes, and capabilities.

I am also convinced that supply chain design and development ought to be thought of as a *meta*-core competency -- the competency of passing judgment on and choosing all other competencies and the strategies for competency development. This approach represents a radical rethinking of supply chain development and its role in business strategy. Furthermore, most managers realize that implementing new ideas into existing business processes can prove to be exceedingly challenging. The good news is that the implementation of clockspeed and 3-DCE ideas does not require radical surgery in organizational processes. This news should come as a relief for the many who have reengineered and been reengineered by managers who insist they must blow up their existing organizations in order to create necessary change.[72]

Instead of such a radical solution, even as an antidote to it, I advocate leveraging one basic organizational methodology, variously referred to as concurrent engineering, the product development process, design-build teams, or integrated product teams (IPTs), as the core of the implementation process for three-dimensional concurrent engineering.

[72] In the words of the chief proponents of reengineering: Managers "must abandon the organizational and operational principles and procedures they are now using and create entirely new ones." See Michael Hammer and James Champy, *Reengineering the Corporation: A Manifesto for Business Revolution* (New York: HarperBusiness, 1993), p. 1.

7.1 The Product Development Process

Especially over the past decade, as clockspeeds in many industries have revved up, many more managers are recognizing the strategic importance of a firm's product development processes. In many industries, product development is the lifeblood of the company. Substantial investment in streamlining and shortening both the product's development time and its time-to-market has taken precedence over many other programs. Competitors with short development cycles and fast industry clockspeeds make a company's survival dependent on its ability to develop products and services rapidly.

As a rule of thumb, many managers assume that as much as 80 percent of life-cycle system design and manufacturing costs are fixed by decisions made during the product development process.[73] This decision making occurs often within the first 20 percent of the design-and-manufacturing life cycle of the product. Furthermore, the eventual product's quality, reliability, serviceability, and overall value as perceived by the customer are also determined at this early stage.

No wonder firms have increased their investment in better product development processes! A good portion of this investment has been directed toward concurrent engineering methods,[74] and their application in the context of the product development process.

In their book *Product Design and Development*, Karl Ulrich and Steven Eppinger present an enlightening table that illustrates the extreme range of complexity in developing manufactured products -- from a Stanley Tools power screwdriver, which requires a development team (both internal and external) of about six people and a development budget of about $300,000, to a Boeing 777 aircraft, which requires tens of thousands of people and a budget approaching $6 billion.[75] Obviously, the organizational tools to be deployed in the screwdriver project would be hopelessly inadequate for developing a jet airplane, whereas the methods employed for the airplane would be hopelessly clumsy and bureaucratic for the screwdriver project. Steven Eppinger, Daniel Whitney, and their MIT students distinguish between what they call "product development in the small" and "product development in the large" to recognize the vast differences between projects such as the Stanley Works screwdriver and the Boeing aircraft.[76]

Where does one draw the line between small and large? If you can get the entire development team (including supply chain members) in a room frequently enough to manage the entire project in a face-to-face manner, then you are in the

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[73] James L. Nevins and Daniel E. Whitney, *Concurrent Design of Products and Processes* (New York: McGraw-Hill, 1989).

[74] See, for example, Mitchell Fleischer and Jeffrey Liker, *Concurrent Engineering Effectiveness* (Cincinnati: Hanser Gardner Publications, 1997).

[75] Karl T. Ulrich and Steven D. Eppinger, *Product Design and Development* (New York: McGraw-Hill, 1994), p. 6.

[76] Steven Eppinger, et al, "A Model-Based Method for Organizing Tasks in Product Development," *Research In Engineering Design*, 1994, No. 6, pp. 1-13.

"small" situation. In contrast, if the team size and distance require communication with layers of organization or heavy use of interactive technology (for example, email and videoconferencing), then you are in the "large" situation.

Most of the formal tools for managing product development projects are relevant conceptually for both small and large teams. However, small-team management can be much more informal about how the structures are used. The discussion in this chapter focuses primarily on "product development in the large," with occasional comments referring to the application to the far simpler case of "small" projects.

7.2 Tools for Product Development Management

For "product development in the large," the complexity of the project often exceeds the analytical capability of any single available tool or perspective. We have all heard the story about the blind men touching various parts of an elephant and trying to make inferences as to what the thing might be. One touches a foot; another, a tusk; another a trunk: Each one, isolated from the others, is mystified about the identity of the whole, until they confer over how the separate pieces produce a solution to the puzzle.

"Product development in the large" requires a similar effort, plus a set of tools, or "lenses," that afford multiple viewing angles from which to gain an appreciation of the entity in all its complexity. A number of tools from multiple perspectives exist for two-dimensional concurrent engineering to support this process, including the various perspectives defined by DFM, project scheduling, design structure, process bottleneck, and customer requirements.

The development process for large products such as automobiles and airplanes is extremely complex. No single tool exists, at present, to address comprehensively the intricacies involved in an automobile development project, for example. Rather, a suite of tools is required. A car development project has to design a product, a process, and a supply chain with staggering complexity: production volumes of up to 1,000 per day, each vehicle comprising over 10,000 parts furnished by thousands of suppliers arrayed in multiple tiers, and production processes utilizing scores of different manufacturing processes and tens of thousands of workers. Managers of "product development in the large" face the challenge of the blind men touching various parts of the elephant: Each has an intimate familiarity with the part or process immediately at hand, but it is very tough to put all the details together in a comprehensive whole.

In this chapter, I describe a number of the tools and perspectives that are productively employed for piecing together the elephant. I describe them both as they currently exist and as they may be extended to focus on supply chain issues and therefore three-dimensional concurrent engineering. In what follows, I will examine five "lenses" to help see the elephant in its totality:

- Design for manufacturability (DFM)

- Project scheduling
- Design structure
- Process bottlenecks
- Customer requirements.

Each of these tools is rich in supporting the management of product development, but will render an incomplete picture if you try to use it alone. The chapter closes with additional suggestions for managing product development and 3-DCE from the vantage point of the combined power of these perspectives.

Design for Manufacturability (DFM)

Much of the benchmarking efforts in the 1980s yielded a near-consensus among American manufacturers that design for manufacturing and its twin, concurrent engineering of product and process, were far superior to throwing the product designs "over the wall." You can come up with the greatest design imaginable for a new product or service, but if you merely throw it over the wall to your production team, they may not have the skills or resources actually to manufacture it. It's hard to imagine anyone ever intentionally creating a dysfunctional process and tossing products over the wall, but it's not atypical for successful companies to grow so rapidly that they do not keep a close eye out for their transition from product development "in the small" to that "in the large."

In a small company, everyone on the product and process development team can meet regularly in the same room. "Can we manufacture this product?" is a question that team members could raise informally, and they could thrash through many of the production issues in an afternoon. As the company grows and expands its production lines, product and process developers move to different departments, different buildings, even different continents. Geographical distance is one challenge to overcome, but more important is the need for more formal approaches to reconcile design-for-product performance with the realities of manufacturability.

In the 1980s, Boothroyd and Dewhurst became well known for their design-for-assembly (DFA) tools for systematically analyzing manufacturability issues in assembly processes.[77] Their work provided "design rules" to help product designers avoid creating designs that were too difficult to build or assemble. In addition, they provided analytic tools to estimate how much it would cost to design and assemble a new product. Later, Ulrich and others pointed out that product development managers needed to assess both assembly and fabrication, as well as both costs and lead time.[78] While researchers added other considerations to the mix, such as designing products that could be upgraded and easily serviced, Boothroyd

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[77] Geoffrey Boothroyd and Peter Dewhurst, *Product Design for Assembly* (Wakefield, R.I.: Boothroyd Dewhurst, Inc., 1989); Geoffrey Boothroyd, Peter Dewhurst, and W. A. Knight, *Product Design for Manufacturing* (New York: Marcel Dekker, 1994).

[78] Karl Ulrich, David Sartorius, Scott Pearson, and Mark Jakiela, "Including the Value of Time in Design-for-Manufacturing Decision-Making," *Management Science* 39.4 (1993): 429-47.

and Dewhurst broke new ground in design for assembly or manufacturing. The tools they developed have helped managers better understand product development "in the large."

Lee and Billington go beyond this classical approach to DFM, adding supply chain issues into design for postponed customization. They describe a case at the Hewlett-Packard Company (HP), which serves as an excellent example of how the design for supply chain cost can be integrated into concurrent engineering.[79] For the European market HP manufactured printers designed with a modular power supply unit that could be customized once customers specified what kind of power supply they needed. This customization design not only reduced HP's inventory costs for that line of printers but also dramatically improved customer service, since customers no longer had to wait as long to receive a printer with a special power unit.

Similarly, in the semiconductor industry, Intel has begun to work aggressively with its equipment suppliers to encourage design for maintainability and serviceability.[80] Depending on the circumstances, Intel may service the product, or the work may be done by the original equipment manufacturer or by a third party. This example suggests other ways that supply chain design can interact with product and process design.

7.2.1.1 Project Scheduling

Probably the most commonly used tool in product development management today is the project scheduling activity chart, known in some circles as PERT (Project Evaluation Review Technique) or CPM (Critical Path Method) or sometimes as PERT/CPM.[81] This tool arrays graphically and sequentially all of the activities required for a project's completion with data on expected completion time and precedence: What activities must precede other activities to develop a "critical path" for the project? The path one follows through these activities is "critical" in that any delay along the path will delay the entire project. Many product development managers use this tool as their primary lever for managing and controlling the project's schedule.

Typically, when a supplier has an essential role, its activity is represented in both the manufacturer's model and its own complex CPM model. What the customer actually sees, however, is only a single activity for the supplier's completed contribution. The supplier's failure to meet the project manager's

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[79] Hau L. Lee and Corey Billington, "Designing Products and Processes for Postponement," *Management of Design: Engineering and Management Perspectives*, ed. S. Dasu and C. Eastman (Boston: Kluwer Academic Publishers, 1994), pp. 105-22.

[80] Morris Cohen and Teck Ho, "Design for Service and Life Cycle Performance: Spares Consumption Reduction and Design for Serviceability," working research agenda, Wharton School, University of Pennsylvania, May 8, 1998.

[81] See, for example, F. K. Levy, G. L. Thompson, and J. D. Weist, "The ABCs of the Critical Path Method," *Harvard Business Review*, September-October, 1963, pp. 98-108.

schedule may come as a rude shock to the customer who has not planned for such a contingency. Toyota, for example, had such a problem with a number of its North American suppliers during the product development and launch process for the 1997 Camry.[82] Late in the program, Toyota received the bad news that suppliers could not meet the schedule requirements. As a result, the auto maker had to move into emergency mode and have the items shipped from Japanese suppliers -- at a much greater cost. The "map" represented by the CPM model traces the route from Point X to Point Y, but it doesn't always tell you how to get around the places where the road has fallen down the mountainside.

By taking the supplier's map, one that shows every activity in the production process, and incorporating it into the customer's map, you can avoid many of the risks and delays inherent in any supply chain. This view into the supplier's production can help you monitor those processes more closely and gain some control over the supplier's ability to fulfill promises. In the case of Toyota, the auto maker went a step further and developed a software domain where the technical development work of a supplier in North America could be observed and tightly integrated with the development work of the Toyota engineers in Japan, in effect substituting electronic proximity for geographic proximity in the supply chain.

This is not micromanaging. It is good business practice that takes advantage of information technology that increases one's knowledge of and participation in those items essential to one's own product development. We should note, however, that such assessments of a supplier's process capability to meet schedule are often possible when the customer is dependent on the supplier only for capacity, but less so if that customer is dependent for knowledge as well.[83]

7.2.1.2 Design Structure

The design structure perspective has been championed and refined by Dr. Daniel Whitney and MIT professor Steven Eppinger, who, with students and colleagues, has built a suite of tools around the design structure matrix (DSM), a diagramming tool for capturing the structure of projects that require many tasks.[84] To construct a DSM, you arrange tasks in a square array that permits task relations to be recorded at various intersections in the diagram. Unlike the critical path method, the matrix can capture iteration, the need to revisit designs and decisions as

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[82] Chris Couch, "Power in the Chain," working paper, Massachusetts Institute of Technology, Cambridge, Mass., 1997.

[83] I am grateful to Dan Whitney for making this point.

[84] Robert P. Smith and Steven D. Eppinger. "Identifying Controlling Features of Engineering Design Iteration," *Management Science* 43.3 (1997): 276-93; Thomas Pimmler and Steven D. Eppinger, "Integration Analysis of Product Decompositions," *Design Engineering* 68 (1994): TK page numbers; V. Krishnan, S. D. Eppinger, and D. E. Whitney, "Accelerating Product Development by the Exchange of Preliminary Information," *ASME Journal of Mechanical Design*, (December 1995) TK volume and page numbers; V. Krishnan, S. D. Eppinger, and D. E. Whitney, "A Model-Based Framework for Overlapping Product Development Activities," *Management Science*, 43.4, (1997): 437-51; V. Krishnan, S. D. Eppinger, and D. E. Whitney, "Simplifying Iterations in Cross-Functional Design Decision Making." *ASME Journal of Mechanical Design* (December 1997): TK volume and page numbers.

new information becomes available. The DSM is especially good at highlighting project tasks that are tightly coupled -- for example, designing and refining components for a highly integral product design.

Fig. 7.1 illustrates the basic DSM tool with a simple example.[85] The process proceeds in two steps, represented respectively by the matrices on the left and right side. The first step is to list all the major activities required in the product development process along both the top and left side. In the figure, these activities are represented by the letters A through L. For each row, an "X" is placed in all columns that have an activity that produces information required for the completion of the activity in that row. On the left side of the matrix, for example, activity E requires information from itself as well as from activities F, H, and K before it can be completed. Gathering information for a large project presents a challenging task, which many organizations are not prepared for, as we have found in several studies of development projects for industrial products.[86]

The DSM matrix also recognizes that some activities are likely to be interdependent. For example, in an airplane development project, the engine specifications are likely to be dependent on the passenger capacity, whereas the passenger capacity will, in turn, be dependent on the available engine power. Such an interdependency is represented in the DSM by having each of these activities receive an "X" in the row of the other. Once this data is collected for all activities, the activities are resequenced by the DSM ordering algorithm[87] and the activities ordered in the most managerially useful sequence.

The resequenced matrix is shown on the right side of fig. 10.1. Because the activity B has no predecessors, it should be undertaken first, then followed by activity C, which has only B as a predecessor. After C, activities A and K may be undertaken simultaneously and independently. After activities A and K are completed, activities L, J, F, and I should be undertaken simultaneously in a highly interactive, concurrent, and iterative manner. The grouping in a single box tells us that these four activities are highly interdependent. High levels of interactive communication are likely to be needed for completion of this set of activities.

An "X" appearing high in the upper right corner of the resequenced matrix (in row A, column H, for example) indicates that iteration back to the beginning is required fairly late in the process. You might think of a situation as representing one very large box such as the one containing L, J, F, and I, but often it is impractical and defeats the purpose of deconstructing the project to treat every activity from A to H in the right-hand matrix as one large concurrent subproject. Rather, when such

[85] This example comes from "Design Structure Matrix Tutorial," Daniel Whitney, Center for Technology Policy and Industrial Development, MIT, 1997.

[86] See, for example, Thomas Black, Charles Fine, and Emanuel Sachs, "A Method for Systems Design Using Precedence Relationships: An Application to Automotive Brake Systems," working paper #3208-90-MS; Thomas A. Black, "A Systems Design Approach to Automotive Brake Design" unpublished thesis, Massachusetts Institute of Technology (Leaders for Manufacturing Program), June, 1990.

[87] Steven Eppinger, et al, "A Model-Based Method for Organizing Tasks in Product Development," *Research In Engineering Design*, 1994, No. 6, pp. 1-13.

instances occur, they represent the need to revisit decision A, in this case to confirm the absence of a major problem. For example, in an automobile development project, suppose A represents the target value for total mass of the vehicle, a design parameter chosen early in the project. Returning to A late in the project is to check, once all the other components have been developed, that the target mass has, in fact, not been exceeded.

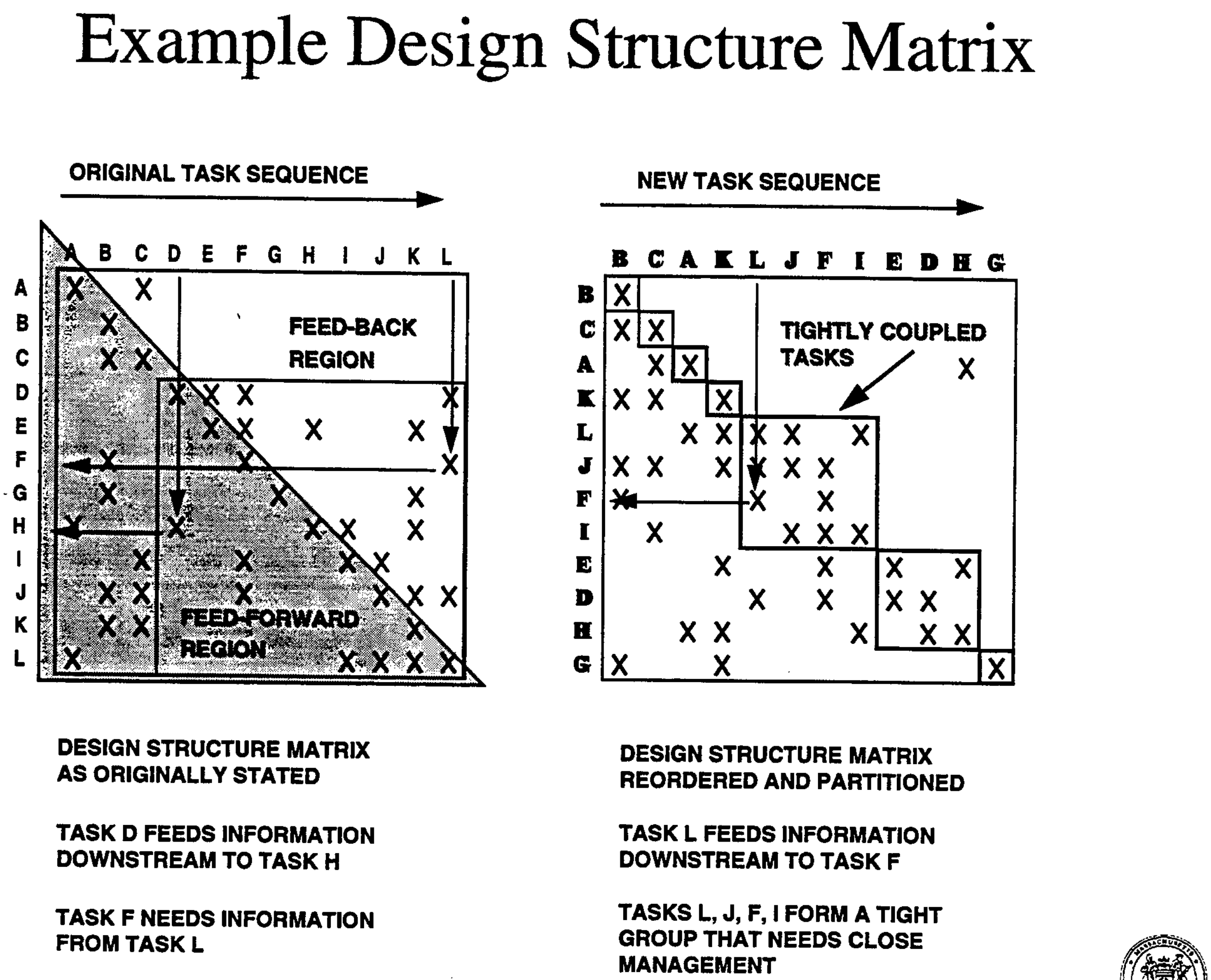

Fig. 7.1. Design Structure Matrix for Representing Complex Design Tasks and Seeking a More Efficient Design Process

When General Motors developed the Oldsmobile Aurora, one of a new generation of luxury cars in the company's fleet, the engineers determined fairly late in the process that the car (as initially developed) was too heavy to give the performance they desired. However, the solution to this problem this late in the project was not to go over every component, shaving off an ounce here, a pound there. Because the problem occurred very late in the Aurora project, engineers did not revisit each item. Rather, they returned immediately to activity "A," assessed the problem, and made one major change: They manufactured the hood out of aluminum rather than steel, thereby shaving many pounds off the design in one (not inexpensive) decision.

This may seem a simplistic example with an "obvious" solution. However, in an actual development project "in the large," a useful DSM has hundreds of activities. Identifying when iteration is most useful, when activities should be done in sequence or in parallel, and when overlapping activities are usefully grouped into one, tightly-coupled, concurrent subproject is virtually impossible without a design structure matrix.

As Steven Eppinger, Daniel Whitney, and their students at MIT have demonstrated repeatedly, DSMs can be used successfully in industries ranging from automobiles to semiconductors, for both product development and concurrent product and process development projects.[88] To extend the DSM tool to supply chain development is not conceptually difficult, but it does demand the same kind of effort required in building a DSM for a product development project. In particular, for suppliers whose contributions are critical to the project under consideration, you should expand the DSM to include those suppliers' activities as though they were seamlessly a part of your overall project. Once you complete your analysis (that is, you compute the matrix on the right side of fig. 7.1), the degree, timing, and type of interaction required with each supplier become all the more evident. If a supplier's activities bunch up in a box like that of activities L, J, F, and I in fig.7.1, then that supplier can work fairly independently once the necessary preceding activities have been completed. If, however, one supplier's activities are tightly intertwined with those of your project or those of another supplier, you will be able to see this logjam at a glance. At that point, you can begin to coordinate the activities of the suppliers in order to avoid as much of the jam as possible. If you see a high degree of interdependence, you may want to rethink whether outsourcing such an integral subproject continues to make sense.

7.2.1.3 Process Bottlenecks

The critical path method and the design structure matrix are designed for and applied primarily to the analysis of a single engineering project. Often, each project within a company is managed by its own project manager, not infrequently a *heavyweight* project manager, as suggested by the lean production paradigm,[89] who may have a great deal of autonomy in managing his or her project, using tools such as CPM and DSM. In such cases, however, there are often resources in the firm that must be shared across multiple projects. For example, in a semiconductor design house, the prototype manufacturing facility is often be shared across all the design

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[88] See references in footnote 12.

[89] James Womack, Daniel Jones, and Daniel Roos, *The Machine That Changed the World* (New York: Rawson Associates, 1990); see also Kim Clark and Takahiro Fujimoto, *Product Development Performance* (Boston: Harvard Business School Press, 1991).

projects. In an automotive company, the clay model shop, where models of the concept vehicles are made, is typically shared by the designers in various divisions, each of which is working on its own projects.

The process bottleneck perspective, explored in work by research teams at MIT and Stanford,[90] reconceptualizes the product development function as analogous to a factory for product development. Instead of focusing on the activities and relationships within the CPM or DSM model for each project, the process bottleneck approach focuses on the resources to be used by all the projects. These resources collectively represent the firm's product development factory. Applying the concepts from Goldratt's "theory of constraints," which states that all factories have a bottleneck (or "constraint") resource,[91] one then looks for the constraint resources in the company's product development "factory."

In the product development context, when multiple projects compete for bottleneck resources, each must wait in queue for its turn to access the constraint capacity. Managing these queues and the relative demand versus supply of capacity at them typically has an enormous impact on the development time of the individual projects. In one study at Polaroid, for example, individual projects under the direction of several project managers working separately were often completed many months, or even years, later than scheduled in the CPM models.[92] Our analysis, using the process bottleneck perspective, concluded that these models had ignored in their calculations the large chunks of time that projects waited for an opportunity to be serviced by the scarce bottleneck resources. Once top management realized that someone in the organization below the level of CEO needed to "own the process" of assessing the capacity levels of various product development resources, the knowledge was available to reduce project completion times significantly.

As important as this insight and accompanying analysis is, its power can be increased by applying it to an integrated 3-DCE framework. In many development projects, supplier contributions can be the bottlenecks. These suppliers serve a large number of projects, sometimes more than one from the same customer. Adding key suppliers as resources in the model and, for those who may be bottlenecks, then managing them as carefully as internal bottlenecks are managed, can have a huge impact on total project time and performance.

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[90] See Robert J. Alexander, "Scheduling and Resource Allocation Methodologies for Fast Product Development in a Multi-Product Environment," unpublished thesis, Massachusetts Institute of Technology (Leaders for Manufacturing Program), June, 1991; Brian Kelly, "Use of a Simulation Game and Queuing Model to Achieve Shorter Lead Times in Stamping Die Development," unpublished thesis, Massachusetts Institute of Technology (Leaders for Manufacturing Program), May, 1996; P. S. Adler, A. Mandelbaum, V. Nguyen, and E. Schwerer, "From Project to Process Management: An Empirically Based Framework for Analyzing Product Development Time," *Management Science* 41,3 (March, 1995): 458-84.; Ibid., "Getting the Most out of Your Product Development Process," *Harvard Business Review*, March-April 1996, pp. 134-52.

[91] Eliyahu Goldratt and Jeff Cox, *The Goal* (Croton-on-Hudson, N.Y.: North River Press, 1984); and Eliyahu Goldratt, *Theory of Constraints* (Croton-on-Hudson, N.Y.: North River Press, 1990).

[92] Alexander, "Scheduling and Resource Allocation Methodologies."

In a research project at General Motors, we analyzed one of the key bottlenecks for the entire vehicle development process: the provision of stamping dies, large steel tools that provide the shape for all stamped metal body parts.[93] Within die development at GM, outsourcing was allowed (by union contract) only if the internal die development capacity was utilized at 100 percent. Individual vehicle program managers typically found that external suppliers provided dies much faster than the internal shop, but were not generally allowed to go outside to other sources. Meanwhile, since the corporate directives loaded the internal capabilities to full capacity, the throughput and delivery times were very high because of the long queues that occurred in the internal operation. By including the supplier capacity in a three-dimensional analysis, we were able to demonstrate how the combined internal and supplier capability could explain and eventually improve performance.

7.2.1.4 Customer Requirements

To be successful, all product development projects need a heavy dose of external reality. Any product whose development does not capture the "voice of the customer" begins life with a huge, frequently fatal handicap. Although this principle seems obvious, many engineering organizations with product development responsibility get so excited about their whiz-bang science and technology that they often neglect to confirm with their intended customers what features and attributes are actually viewed as desirable and worth paying for.

The best-known tool for the customer-requirements perspective in product development is Quality Function Deployment (QFD),[94] another import from Japan that came to the West during the great wave of immigration of Japanese management thinking in the 1980s. One of its early proponents and exponents in the United States was Don Clausing of Xerox, later at MIT.[95] QFD offers a tool called the "house of quality," a name derived from the analytical diagram that resembles a box with a slant roof. It offers a high-level overview of a range of issues in customer-driven product development, including identification of key product features, relation of these features to perceived customer requirements, identification of product technologies for their delivery, and assessment of competing products.

Two related tools, "concept engineering" and "key characteristics," have grown out of the QFD and customer requirements perspective to add more depth to the house-of-quality approach for integrating formally and systematically the voice of the customer into the product development process.

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[93] Kelly, "Use of a Simulation Game and Queueing Model."

[94] John Hauser and Don Clausing, "The House of Quality," *Harvard Business Review* 66.3 (1988): 63-73.

[95] Idem. See also Donald Clausing, *Total Quality Development: A Step-by-Step Guide to World-Class Concurrent Engineering* (New York: ASME Press, 1994).

7.2.1.5 Concept Engineering[96]

Concept engineering is a structured process, with supporting decision aids, for developing product concepts by a product development team.[97] The process alternates between the level of thought (reflection) and level of experience (data) in a way that allows participants to understand what is important to the customer, why it is important, how it will be measured, and how it will be addressed in the product concept. As presented in fig. 7.2, concept engineering has five stages each with three steps.[98]

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[96] See Gary Burchill and Diane Shen, "Concept Engineering: The Key to Operationally Defining Your Customer's Requirements" (Cambridge, Mass.: Center for Quality Management, 1992); Gary Burchill, "Concept Engineering: An Investigation of TIME vs. MARKET Orientation in Product Concept Development," unpublished doctoral thesis, Massachusetts Institute of Technology, 1993; Gary Burchill, "Concept Engineering: A Complete Product-Concept Decision-Support Process," *Design Management Journal* (Fall, 1993): 78-85. See also Gary Burchill and Charles Fine, "Time Versus Market Orientation in Product Concept Development: Empirically-based Theory Generation," *Management Science* Vol. 43, No. 4, (April 1997): 465-78.

[97] Ulrich and Eppinger provide a similar model in *Product Design and Development.*

[98] More complete documentation is available from the Center for Quality Management at (617) 873-8950 or at http://www.cqm.com/.

Concept Engineering

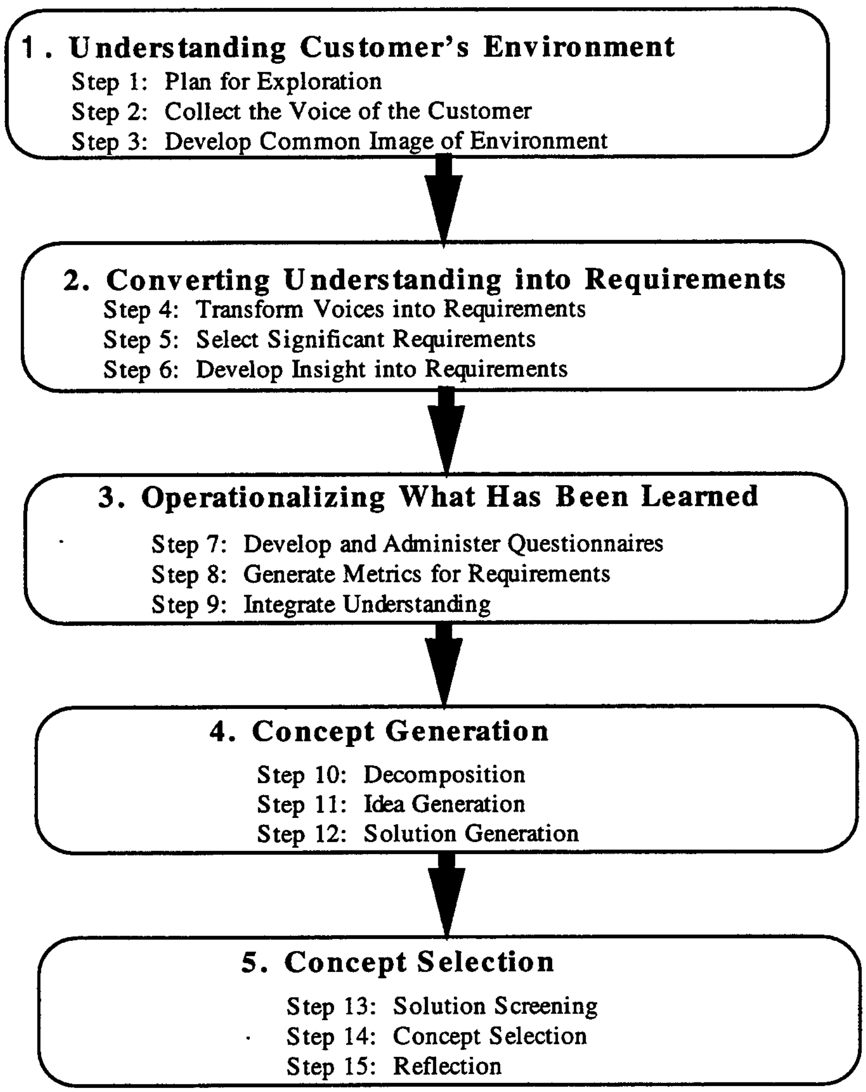

Fig. 7.2. The Five Stages and 15 Steps of Concept Engineering

7.2.2 Stage 1: Understanding the Customer's Environment *Stage 2: Converting Understanding into Requirements*

In stage 1 the team develops empathy for the customer in the actual use environment of the product or service. Images of the customer's use environment are selected and analyzed with a KJ diagram.[99] This "Image KJ" visually and verbally links the product concept to the customer's real world and provides the product development team members a common map, to help visualize the customer's environment for the product concept decisions.

7.2.3 *Stage 2: Converting Understanding into Requirements*

Stage 2 distills a small set of well-understood, carefully articulated, critical requirements for the customer. The customer's language, often laden with subjective wording, is converted into an objective, fact-oriented requirement statement better suited for use in downstream development activities. A small set of the vital few requirements, taken from the useful many, is selected. The relationships among them are then analyzed.

7.2.4 *Stage 3: Operationalizing What Has Been Learned*

In stage 3, the team validates the customer's key requirements, operationally defined in measurable terms and displays them so that the relationships among requirements, metrics, and customer feedback are easily seen.

7.2.5 *Stage 4: Concept Generation*

This stage marks the transition in the development team's thinking from the "requirement or problem space" to the "idea or solution space." The complex design problem is decomposed into subproblems based on perspectives of both the customers and the design engineers. Through individual and group collaboration efforts, the team creates first individually, and then collectively, solution concepts from which the final design concept will be developed.

7.2.6 *Stage 5: Concept Selection*

The final stage of concept engineering builds on a method known as "concept selection,"[100] an iterative process of combining and improving initial solution concepts to develop a small number of superior concepts. The "surviving" complete concepts are evaluated in detail against customer requirements and organizational constraints in order to select the dominant concept(s). When completed, an audit trail exists for tracing the entire decision process as the concept engineering process is self-documenting.

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[99] KJ diagrams structure detailed language (vs. numerical) data into more general conclusions using semantic and abstraction guidelines. They are one of a family of tools invented by Jiro Kawakita and known as the KJ method. See Jiro Kawakita, *The Original KJ Method* (Tokyo: Kawakita Research Institute, 1991).

[100] Stuart Pugh, *Total Design* (Workingham, England: Addison-Wesley, 1990); see also ibid., "Concept Selection: A Method That Works," International Conference on Engineering Design, Rome, Italy, 1981.

Key Characteristics[101]

Key characteristics are typically defined as features of the product or process that are perceived to be critical to delivering value to the final customer. The essence of the key characteristics tool is the flowdown of requirements, from customer needs to manufacturing requirements to support those needs, to manufacturability requirements to support the manufacturing function. In many applications, subdividing these into product key characteristics (PKCs), manufacturing key characteristics (MKCs), and assembly key characteristics (AKCs) has proved to be a useful characterization.[102] PKCs are associated with the important properties of the product that create customer satisfaction. MKCs are associated with the manufacturing processes that create the detail level PKCs. AKCs are those features required to support assembly (or manufacturability) of the product. Fig. 7.3 illustrates how product, manufacturing, and assembly are related.[103] KC's are covered in much greater depth in the sister Aero report.

[101] For detailed references, see Don Lee, Anna Thornton, and Timothy Cunningham, "Key Characteristics for Agile Product Development and Manufacturing," Agility Forum Fourth Annual Conference Proceedings, March, 1995; Don Lee and Anna Thornton, "The Identification and Use of Key Characteristics in the Product Development Process," ASME Eighth Design Theory and Methodology Conference, August, 1996; Timothy Cunningham, Don Lee, Ramakrishnan Mantripragada, Anna Thornton, and Daniel Whitney, "Definition, Analysis, and Planning of a Flexible Assembly System," proceedings of the Japan/United States Symposium on Flexible Automation, ASME, June, 1996.

[102] Lee and Thornton, "The Identification and Use of Key Characteristics."

[103] Idem.

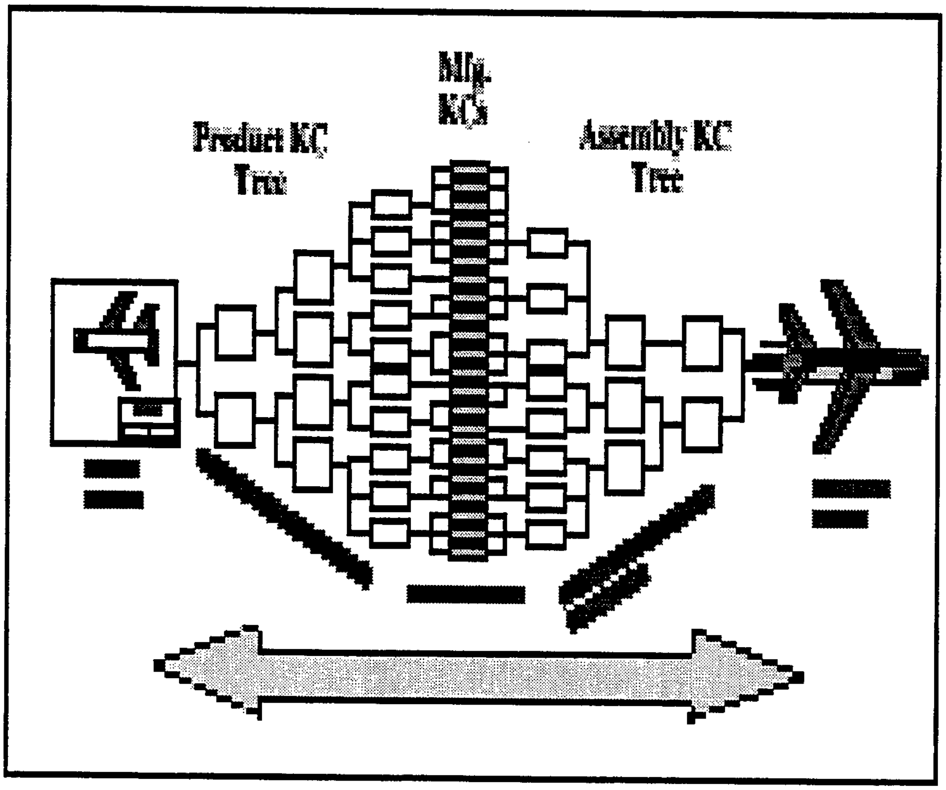

Fig. 7.3. The Relationship among Product, Manufacturing, and Assembly: Key Characteristics

At the far left of the diagram is the final product delivered to the customer, including those PKCs or features he or she desires. MKCs are the features of the manufacturing system that are required to deliver the PKCs from the factory to the product. Thus MKCs flow from the PKCs. On the right side of fig. 10.3 are the AKCs, those features that support assembly and manufacturability of the product.

MKCs support the manufacturing organization's delivery of special product features. For example, if a customer wants a disk drive in her laptop PC that holds ten gigabytes of data (the PKC), then certain manufacturing tolerances (MKCs) must be achieved in the disk-making technology to make such a product feasible. AKCs, on the other hand, are features directed toward design for assembly. For example, if the disk drive has features that allow it to snap-fit directly into the laptop frame, assembly is less costly and less prone to defects than it would be if the design relied on screws for the assembly process.

The key characteristics approach supports a range of decisions within the product and process development process, including feature choice, detailed product design, and equipment choice. The 3-DCE approach pushes firms to extend this tool to include supplier key characteristics (SKCs) by flowing the requirements outside of the customer's firm into the value chain. The key characteristics tool can be used to help identify key features on supplied subsystems, key capabilities in suppliers' factories, and key components from the suppliers' supply chains.

For example, consider what happened to a product design at Intel when the company included supply chain issues in a 3-DCE effort. As Intel has worked to add more functionality to its products, the company has planned expansion of the features of the key product from a stand-alone microprocessor to a circuit board with a mounted microprocessor supported by other electronic components. In the design of the expanded product, Intel had historically used a mounting system that relied on nine small machined metal pins to support contact between the chip and the board. Annual sales volumes of the new product were expected to be approximately 100 million units; thus, 900 million machined metal pins would be needed. Exploration of the capacity characteristics by Intel's supply chain team revealed that there were not enough of the required type of machine tools for making 900 million machined pins *in the entire world!*[104] Needless to say, this work on the key supply chain characteristics, done early in the design process so that the product features could be redesigned, prevented what could have been a disaster for one of Intel's key product launches.

7.3 The growing importance of CE tools

Many of these product development management tools do not have household names. Historically they have been part of engineering project managers' purview, not that of general business unit managers. Let me suggest three reasons, however, why *all* managers need to become more familiar with this toolkit.

1. The increasing clockspeeds in our economy are forcing firms to launch products more frequently. As a result, a larger fraction of the total work in the firm is project work.[105] In effect, then, the business manager becomes a project manager or an overseer of project managers for a larger fraction of his or her job and career. The premium paid for project management skills and tools is thus likely to increase.
2. Those faster clockspeeds are also forcing companies to compress their product development cycles. One important strategy for cycle compression is to perform historically sequential activities in parallel. Concurrent engineering accomplishes this goal. Thus, more companies are finding that concurrency is a necessity and that more managers will have to learn concurrent engineering tools.

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[104] This anecdote was related to me by Randy Bollig, Director of Corporate Capital Equipment at Intel, July 17. 1997.

[105] Geoffrey Parker, "*Contracting for Employee and Supplier Capability Development*," unpublished dissertation, Massachusetts Institute of Technology, Cambridge, Mass., 1998. Parker discusses the evolution of the economy to more project work and the implications of that change for supply chain relationships.

3. When one comes to view supply chain design as the competency of choosing all other competencies, then supply chain design becomes the purview of senior management. However, once one understands the inseparability among supply chain architecture, process architecture, and product architecture, greater communication between senior strategists and project managers becomes essential. As a result, all will need to understand the tools of product development management in order to have a common language with which to discuss issues and solve problems related to the product, process, and supply chain architectures.

8. Methodology Synthesis for Clockspeed-based Strategic Supply Chain Design and 3-DCE

This report concludes with a synthesis of the methodology inherent in the preceding sections.

Table 12.1: Summary Methodology for Clockspeed-based Strategy

	Action	Discussed in Sections(s)	Examples
Step 1	Benchmark the fruit flies of fast-clockspeed industries	4	Intel Compaq Dell Information-entertainment
Step 2	Understand, map and assess the supply chain. Three chain maps: • Organization • Technology • Capability	5	Chrysler Dell

Step 3	Apply clockspeed analysis (dynamic chain analysis) • Double helix • Chain clockspeed analysis	5	Defense aerospace Information-entertainment
Step 4	Exploit and execute 3-DCE and competency development dynamics •3-D architecture • Tools for Product Development and Concurrent Engineering	6,7	Defense aerospace Information-entertainment

Following the example of the biologists, step 1 in the methodology benchmarks the fruit flies, as discusses in section 4. Observing the dynamics of fast-clockspeed industries enables managers to discover patterns of evolution more quickly and apply them more readily to their particular situations. In addition, given the acceleration of clockspeeds almost everywhere, the fruit flies provide a glimpse of what future life may be like for a wide variety of industries.

In step 2, you work to comprehend the complexities and dynamic forces within your industry and create maps of your organization's supply chain -- all the way downstream to the final customer and all the way upstream to knowledge creation and mineral extraction. As section 5 discusses, these maps should take into account at least three views of the chain: those of the organization, of technologies, and of the network of capabilities. Drawing the chain from all three viewpoints is extremely challenging, but often managers discover important links, just as the managers at Chrysler found when they visited the casting clay supplier several tiers removed their principal operations.

Step 3 applies the clockspeed concept to the chain maps of step 2. Understanding the clockspeeds in your environment is critical. The double helix decodes the rates and directions of change in industry structures -- from vertical/integral to horizontal/modular and back -- proving an indispensable guide in making decisions about how best to invest in the capability chain. The clockspeed analysis of the chain maps, illustrated for defense aircraft and information-entertainment in section 5, provides a tool to support strategic assessment of capability ownership or outsourcing along the entire chain.

In step 4, you begin to execute the capability development process through the use of three-dimensional concurrent engineering (3-DCE) described in section 6.

Analysis of product, process, and supply chain architectures enables you to sharpen your analysis of a strategy for outsourcing certain components if necessary. You then can begin implementing your decisions within the framework of existing concurrent engineering tools (section 7), provided that strategic thinking authority is integrated within the concurrent engineering processes.

9. Appendix 1. Outline of course in Three-Dimensional Concurrent Engineering (developed in collaboration with Dr. Daniel Whitney)

This appendix contains information about a course in Three-Dimensional Concurrent Engineering that was developed during the research, and taught three times at MIT, most recently in Spring of 1998.

COURSE OUTLINE

Manufacturing Policy 15.769 ***Tuesdays, 2:30-5:30***

E51-145 & E51-325 Prof. C. Fine

Date *Subject* *Materials, Readings*

I. PROCESS DESIGN

3-Feb Mfg Strat Intro ***POMS* SPECIAL ISSUE**
Guest Lecture **John Swanson, VP Qualcomm**

10-Feb Fast, Flexible, & Agile Manufacturing **Lilly, US Robotics, Economist, Upton**

Readings:
Economist survey
Upton, D. M., What Really Make Factories Flexible?, *HBR*, 73(4), 1995
Upton, D. M., The Management of Manufacturing Flexibility, *California Management Review*, 36(2), 1994.

Case 1: Eli Lilly and Co.: The Flexible Facility Decision
Questions for the case:

How has the competitive environment in pharmaceuticals been changing over the past few years? What are the implications for the role of manufacturing within Eli Lilly?

How does each facilities option affect Lilly's cost structure capacity management and product development capabilities? For what type of products does the proposed flexible facility provide an efficient (i.e., low cost) manufacturing capability?

What type of flexibility does the "flexible facility" provide? What is the value of this flexibility to Eli Lilly? How much is Lilly paying for this flexibility?

Given Lilly's strategic goals in the 1990s, which option should Steve Mueller recommend? Are there other options that Lilly should be contemplating? If so, what are they?

Case 2: US Robotics Inc.

Questions for the case:

Why does US Robotics need "5 by 5?" Why have so many firms failed at $100m sales, and how could USR avoid such a fate? What kinds of strategic flexibility are important to USR and how should it maintain them?

Should US Robotics have an explicit manufacturing strategy? If so, what should it be?

What will be the most important types of short-term flexibility for US Robotics? How will the manufacturing strategy you outlined support this?

How will you grow US Robotics Operations? Will you break up the business as it becomes necessary to move to multiple sites? If so, how? - by function? by market? by manufacturing technology?

In general, how does a company stay flexible? Can a company become agile?

II. SUPPLY CHAIN DESIGN

24-Feb	**Clockspeed-based Supply Chain Design**	**Fine: Chaps 1,2,3,4,5, Fine/Whitney**

Readings:

Please read the draft chapters 1-5 (pp. 2-57) from my forthcoming book, *CLOCKSPEED: WINNING INDUSTRY CONTROL IN THE AGE OF TEMPORARY ADVANTAGE.* Also read the first 24 pages of "Is the Make-Buy Decision Process a Core Competence," by Fine & Whitney.

Class Preparation:

Come to class prepared to address:

1. How have firms typically thought strategically about product and process design? How have firms typically thought strategically about supply chain design? Does the framework in *CLOCKSPEED* provide a whole new way of thinking, a new wrinkle on the old ways of thinking, or merely a re-hash on existing ways of thinking. Try to come up with at least one argument to support each of these possibilities.

2. ***Hand-in assignment (teams of up to four people OK):*** List ten industries with which you have some interest and/or familiarity in order of increasing clockspeed (by your own guestimation). For each see if you can name at least one measure for each of product technology clockspeed, process technology clockspeed, and organizational clockspeed. Based on your knowledge of each industry, is there any evidence of a cycling between a vertical/integral structure and a horizontal/modular structure? List five organizational strategies for coping with increasing clockspeeds.

3-Mar	**Lean Supply Chains**	**Clark, Fujimoto, Lariviere, Cusumano, Takeishi, Nobeoka**

Clark (1989) "Project Scope and Project Performance: The Effect of Parts Strategy and Supplier Involvement on Product Development," Management Science

Fujimoto (1994) "The History and Origins of Black Box Practices in the Japanese Automotive Industry," Tokyo University working paper 94-F-1. (skim)

Takeishi and Cusumano, "Supplier Relations and Management: A Survey of Japanese, Japanese-Transplant, and U.S. Auto plants."

Lariviere, M. (1995) "Worldwide Purchasing at General Motors."

Nobeoka, K. (1995), "Alternate Component Sourcing Strategies within the Manufacturer-Supplier Network," Kobe University Discussion Paper #54.

10-Mar Make/Buy, Supply Chain Design — Fine, Chap 9; Welch/Nayek; Venkatesan, Huber, Quinn/Hilmer

Fine, C.H., Clockspeed, Chapter 8: Make vs. Buy

Welch, J.A. and P.R. Nayak (1992), "Strategic Sourcing: A Progressive Approach to the Make-or-Buy Decision," *Engineering Management Review*, Fall.

Huber, R. (1993), "How Continental Bank Outsourced Its 'Crown Jewels'," Harvard Business Review, Jan-Feb.

Venkatesan, R. (1992), "Strategic Sourcing: To Make or not to Make," *Harvard Business Review*, Nov/Dec 1992.

Quinn, J.B., and F.G. Hilmer, "Strategic Outsourcing," SMR, Summer 94

III. PRODUCT DESIGN

17-Mar Product Architecture — Ulrich, Henderson/Clark, Sjostrom Christiansen, Fine Ch 8, Farrell,et al

Karl Ulrich, "The Role of Product Architecture in the Manufacturing Firm," *Research Policy*, Vol. 24, p. 419-440, 1995.

Sjostrom, S. , "The Modular System in Truck Manufacturing," *Griffen*, Nov. 1990.

Henderson, R., and K. Clark, "Architectural Innovation: The reconfiguration of existing product Technologies and the failure of established firms," *ASQ*, 35, pp. 9-30, 1990.

Fine, C.H., *Clockspeed*, Chapter 7: Three-Dimensional Concurrent Engineering

G. Saloner, H. Monroe, J. Farrell (1994), "The Vertical Organization of Industry: Systems Competition Versus Component Competition," forthcoming, *Journal of Economics and Management Strategy*.

Christensen, C. (1994), "The Drivers of Vertical Disintegration," Harvard Business School working paper.

31-Mar **Dynamics of Standards** **Arthur, David, Farrell/Saloner Morris/Ferguson**

and Schrage **Prototyping** **Ulrich/Eppinger; Bowen, et al;**

Paul A. David, "Clio and The Economics of QWERTY," American Economic Review, Vol 75, No. 2, 1985, pp. 332-337.

Brian Arthur in "Competing Technologies, Increasing Returns, and Lock-in by Historical Events," in *The Economic Journal*, Vol. 99, March 1989, pp.116-131

Farrell, J. and G. Saloner (1985), "Standardization, Compatibility, and Innovation," *Rand Journal of Economics*, Spring 1985, 70-83.

Morris, Charles R. and Charles H. Ferguson (1993, March-April) "How Architecture Wins Technology Wars, *Harvard Business Review*, 86-96.

"Effective Prototyping" - Chapter 10 of *Product Design and Development* by K. Ulrich & S. Eppinger. McGraw Hill, 1995.

"Prototyping: Rapid Learning and Early Testing" - Chapter 7 of *The Perpetual Enterprise Machine: Seven Keys to Corporate Renewal Through Successful Product and Process Development* by Bowen, Clark, Holloway, & Wheelwright. Oxford University Press, 1994.

"The Culture of Prototyping,"by Michael Schrage from *Design Management Journal* Winter 1993.

7-Apr Whitney **Product Development Management** **Ward, et al, Burchill/Fine, Leonard-Barton, BMW**

Ward, A., Liker, J.K, Christiano, J.J., Sobek, D.K., "The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster," SMR, Spring 1995, pp. 43-61.

Burchill, G. and C. Fine , "Time versus Market Orientation in Product Concept Development: Empirically-based Theory Generation," *Management Science., 1997.*

Whitney, D. (1993). Nippondenso CO. LTD.: A Case Study of Strategic Product Design, *Research in Engineering Design*, vol. 5, no. 1, pp. 1-20.

Leonard-Barton, D. (1992), "Core Capabilities and Core Rigidities: A Paradox in Managing New Product development," SMJ, 13:111-125.

Case - BMW: The 7-Series Project (A), (B). (Case B will be distributed in class)
Questions for the case:
How does BMW define quality?
What are the causes and consequences of BMWís quality problems with newly launched products? What should be done to improve launch quality?
What are your recommendations to Carl-Peter Forester concerning the R-series prototypes? What should he do regarding future development projects?
What changes would you recommend in the way BMW develops new models? What attributes of newly launched products would you expect to improve as a result of these recommendations? Which attributes might deteriorate?
What recommendations would you make to Chairman von Kuenheim regarding BMW's strategy to compete against new Japanese entrants into the luxury car market?

IV. INTEGRATED 3-D DESIGN

14-Apr	Aircraft Industry	VISITOR: D. Whitney
28-Apr	(Multi-media, Information, Communications & Electronics)	"Bio of a Killer Technology," VISITOR: L. Kimerling?
7-May	Autos: Globalization, Environment, & Technology (NOTE: CLASS IS ON THURSDAY THIS WEEK.)	VISITOR: J. Kassakian
12-May	Commercial Aerospace meets M.I.C.E.	Fine: Chaps 11,12 Wireless in Seattle: Boeing/Teledesic

notes: Feb 17 has a Monday schedule throughout MIT due to Feb 16 holiday.

Mar 24 is spring break week
April 20-21 is Patriots' Day holiday